Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
2013

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Doutor Mário Lima (orientador), Professor Auxiliar e do Doutor António Teixeira (coorientador), Professor Associado ambos do Departamento de Eletrónica, Telecomunicações e Informática e do Instituto de Telecomunicações - Aveiro.

Dedico este trabalho aos meus pais Adolfo Jorge e Maria de Lurdes e aos meus colegas, amigos e familiares que me apoiaram ao longo deste percurso.

o júri / the jury

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palavras-chave GPON, NGPON2, WDM-PON, SFPs.

resumo

Com o aumento da necessidade de largura de banda nos últimos anos as redes de acesso encontram-se em constante evolução. Sendo que as redes GPON são de momento a principal escolha num âmbito europeu, devido ao aumento de tráfego nos últimos anos, a necessidade de uma nova tecnologia para redes de acesso NGPON2 é um dos principais focos de investigação em telecomunicações.

Neste documento irá ser realizado um estudo das actuais redes PON e as possíveis opções para uma rede NGPON2. Maior ênfase será dado à possibilidade de realizar uma rede WDM-PON utilizando como base a arquitectura GPON já implementada.
.
Utilizando SFPs irá ser demonstrado como é possível converter uma transmissão GPON para outros comprimentos de onda com o objectivo de criar uma rede WDM.

keywords GPON, NGPON2, WDM-PON, SFPs.

abstract

Due to the increased need for more bandwidth, access networks are evolving constantly. At the moment, GPON networks are the main choice in Europe, but due to the increased traffic in recent years, developing a new option for access networks defined NGPON2 as one of the main focuses in telecommunication research.

In this document the current PON networks and the possible NGPON2 candidates will be studied. The main focus will be the possibility of designing a WDM-PON network while maintaining the main GPON architecture already implemented.

By using SFPs, an example will be shown where a normal GPON transmission will be converted to another wavelength in order to show a possible implementation of a WDM network.

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List of Acronyms

10GPON	-	10 Gigabit Passive Optical Network
10G-EPON	-	10 Gigabit Ethernet Passive Optical Network
ASE	-	Amplified Spontaneous Emission
APD	-	Avalanche Photodiode
APON	-	Asynchronous Transfer Mode Passive Optical Network
ATM	-	Asynchronous Transfer Mode
AWG	-	Array Waveguide Grating
BER	-	Bit Error Rate
BERT	-	Bit Error Rate Tester
BPON	-	Broadband Passive Optical Network
CDR	-	Clock/Data Recovery
CML	-	Chirp Managed Laser
CMOS	-	Complementary Metal-Oxide-Semiconductor
CO	-	Central Office
CWDM	-	Coarse Wavelength Division Multiplexing
DBR	-	Distributed Bragg Reflector
DFB	-	Distributed feedback laser
DPSK	-	Differential Phase-Shift Keying
DWDM	-	Dense Wavelength Division Multiplexing
ECL	-	External Cavity Laser
EDC	-	Electronic Dispersion Compensation
EPON	-	Ethernet Passive Optical Network
FSAN	-	Full Service Access Network
FTTB	-	Fiber-to-the-Building
FTTC	-	Fiber-to-the-Curb
FTTH	-	Fiber-to-the-Home
FTTx	-	Fiber-to-the-x
GEM	-	GPON Encapsulation Method
GPON	-	Gigabit Passive Optical Network
GTC	-	GPON Transmission Convergence
ID	-	Identifier
IEEE	-	Institute of Electrical and Electronics Engineers
IL FP	-	Injection Locked Fabry-Perot
IP	-	Internet Protocol
IRZ	-	Inverse Return Zero

ITU	-	International Telecommunication Union
LED	-	light-emitting diodes
MEMS	-	Microelectromechanic System
MSM	-	Metal-Semiconductor-Metal
NGA	-	Next Generation Access
NGPON	-	Next-Generation Passive Optical Network
NRZ	-	Non-Return-to-Zero
ODN	-	Optical Distribution Network
ODSM-PON	-	Opportunistic and dynamic spectrum management PON
OLT	-	Optical Line Terminal
ONU	-	Optical Network Unit
ONT	-	Optical Network Terminal
OSA	-	Optical Spectrum Analyzer
OSR	-	Optical Spectrum Reshaper
PCBd	-	Physical Control Block downstream
PLOu	-	Physical Layer Overhead upstream
PON	-	Passive Optical Network
PPG	-	Pulse Pattern Generator
PRBS	-	Pseudo Random Bit Sequence
ROP	-	Received Optical Power
RSOA	-	Reflective Semiconductor Optical Amplifier
SCM	-	Signal Code Modulation
SFP	-	Small Form-Factor Pluggable
SLD	-	Super-Luminescent Laser Diode
SLED	-	Superluminescent light-emitting diodes
T-ECL	-	Tunable External Cavity Laser
TDM	-	Time Division Multiplexing
TIA	-	Trans-Impedance Amplifier
TL	-	Tunable Laser
TWDM-PON	-	Time and Wavelength Division Multiplexed PON
Tx/Rx	-	Transmit/Receive
VCSEL	-	Vertical-Cavity Surface-Emitting Laser
VOA	-	Variable Optical Attenuator
WBF	-	Wavelength Blocking Filter
WDM	-	Wavelength Division Multiplexing
WDM-PON	-	Wavelength Division Multiplexed Passive Optical Network
XG-PON	-	10 Gigabit Passive Optical Network

1. Introduction

1.1 Context and Motivation

As the amount of internet services provided increases, so does the need for higher bandwidth and transmission rate for access networks responsible for delivering all this information. In this context, new solutions were necessary which led to the development of PON. This solution was a major improvement due to the higher transmission rate and all optical network using only passive elements.

A PON is a point to multipoint network architecture where a single fiber connects the OLT (Optical Line Terminal) and is then divided to the different ONUs (Optical Network Unit) by a splitter. As this is a passive network there is no need for an external power supply in the path between the OLT and ONUs resulting in reduced costs compared to active networks.

The downstream signal is transmitted to all ONUs and then filtered based on the port ID (Identifier), while for the upstream signal, a different time slot is assigned to each ONU by the OLT. This type of bandwidth management is called TDM (Time Division Multiplexing).

Figure 1, shows an example of a PON network. As described above, the signal being transmitted by the OLT is sent to every ONU and each of these chooses the information it needs based on the identifier.

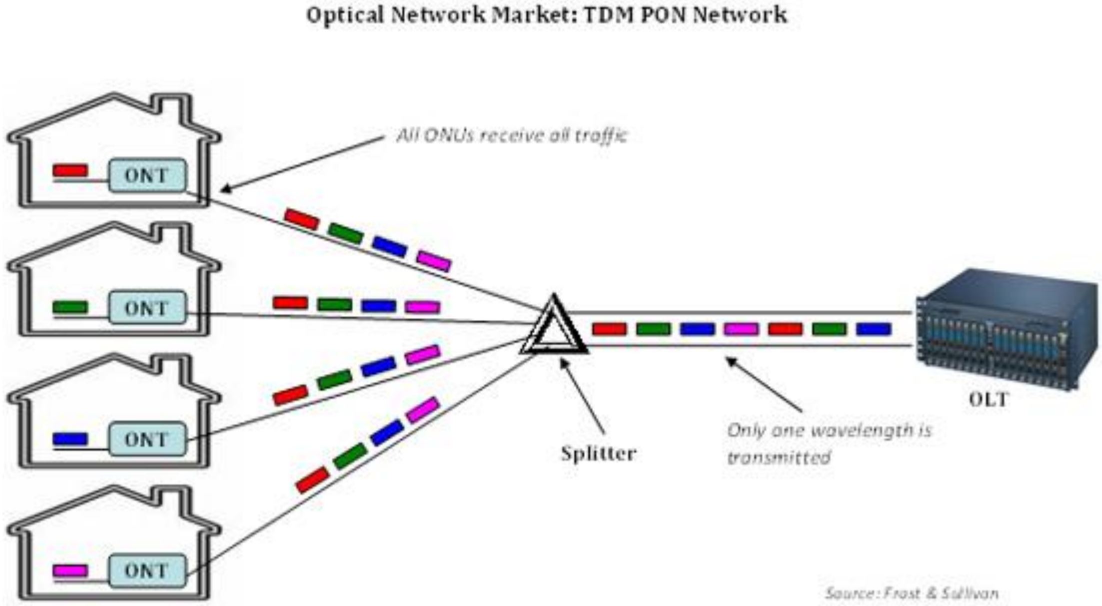


Figure 1: Passive Optical Network (PON) [1]

The PON network had several developments since research was started in the 90's.

The first standardized PON was called APON (Asynchronous Transfer Mode Passive Optical Network) developed by FSAN (Full Service Access Network) and based on the G.983 ITU-T (International Telecommunication Union) standard. It was soon improved and the standard was later revised introducing the BPON network. The transmission rates for the BPON (Broadband Passive Optical Network) network were 622.08 Mbit/s downstream and 155.52 Mbit/s upstream.

As the internet boomed there was an exponential increase in IP (Internet Protocol) traffic leading to a need for more efficient protocols. The ATM (Asynchronous Transfer Mode) protocol is inefficient in transporting IP traffic and as such in the early 2000's ITU-T approved the G.984 standard leading to a GPON network. This technology was a massive improvement both in total bandwidth and its efficiency using 2.5 Gbit/s for downstream transmission and 1.25 Gbit/s for upstream.

Similar to the GPON, an alternative was developed by IEEE (Institute of Electrical and Electronics Engineers) called EPON (Ethernet Passive Optical Network) using symmetric transmission rates of 1 Gbit/s. Unlike the GPON which was massified in Europe and North America, EPON is mostly used in Asia.

As the need for greater transmission rates increased in the late 2000's new long term options were necessary and as such 10GPON (10 Gigabit Passive Optical Network) and 10G-EPON (10 Gigabit Ethernet Passive Optical Network) were developed using the same principles as its predecessors but with the option of having up to 10 Gbit/s symmetrical bandwidth.

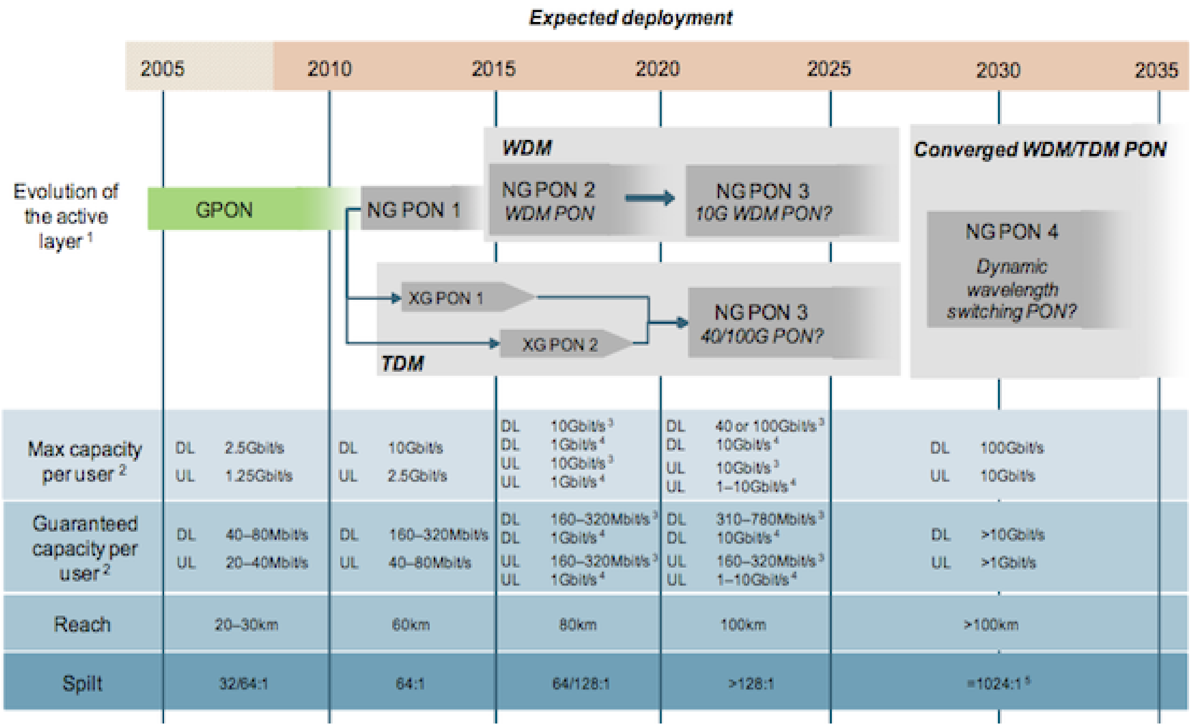


Figure 2: PONs future (source: Analysys Mason) [2]

As shown in Figure 2, due to the ever increasing need for more bandwidth in the future, network solutions will need to migrate to a WDM solution so several wavelengths may be transmitted in the same fiber leading to an increase in bit rate.

1.2 Objectives

The main purpose of this document is to describe the PON (Passive Optical Network) technology and its evolution leading to the present scenario where a WDM (Wavelength Division Multiplexing) based PON network is in the forefront of the research efforts in developing new technologies to support the rapid growth of internet and multimedia services.

In order to better fulfill the purpose of implementing new WDM technologies on current networks, this dissertation will demonstrate a possible solution using available equipment.

1.3 Structure

First, the principles and reasons for the development of PON networks will be described by studying its main characteristics and how they evolved.

In chapter 2 a more in depth study of the current PON technologies is done by analyzing the GPON (Gigabit Passive Optical Network) network and its variants, namely the XG-PON (also known as 10 Gigabit Passive Optical Network). After describing thoroughly how a GPON system works, a similar analysis will be done for the XG-PON2 networks, with the main focus being on a WDM-PON network.

Chapter 3 describes the main components in a WDM-PON (Wavelength Division Multiplexed Passive Optical Network) network by analyzing how the tunable lasers and receivers work. Besides analyzing a WDM-PON using tunable components there will also be an introduction to how SFPs work and their importance.

Chapter 4 consists of a brief description of the equipment used in the laboratory experiments by referring their main characteristics and functionalities.

Chapter 5 shows the results obtained in the laboratory. These consist of tests done using a GPON network, a wavelength converting network using SFPs and results provided in the EPON manual in order to compare to the results obtained on the GPON.

Chapter 6 is the second half of the work done in chapter 5. After having obtained certain results on the laboratory, in this chapter similar tests are done using VPI transmission maker.

1.4 Main Contributions

In the author's opinion, the main contributions of this document are as follows:

- Description of the main characteristics of current and previous PON networks by analyzing their main advantages and drawbacks.

- Analysis of possible solutions for a NGPON2 network solution with greater emphasis on WDM-PON.

- Laboratory tests with a GPON network and a possible implementation for a WDM-PON solution using available equipment.

- Simulations performed in order to confirm laboratory results and better characterize the benefits of using a wavelength conversion network using SFPs.

2. Current PON Solutions

Currently, as more operators are changing to a FTTH (Fiber-to-the-Home) solution, PON networks are becoming the standard for access networks. The most used solutions at the moment are the GPON and EPON.

Figure 3 shows an example of a FTTH solution.

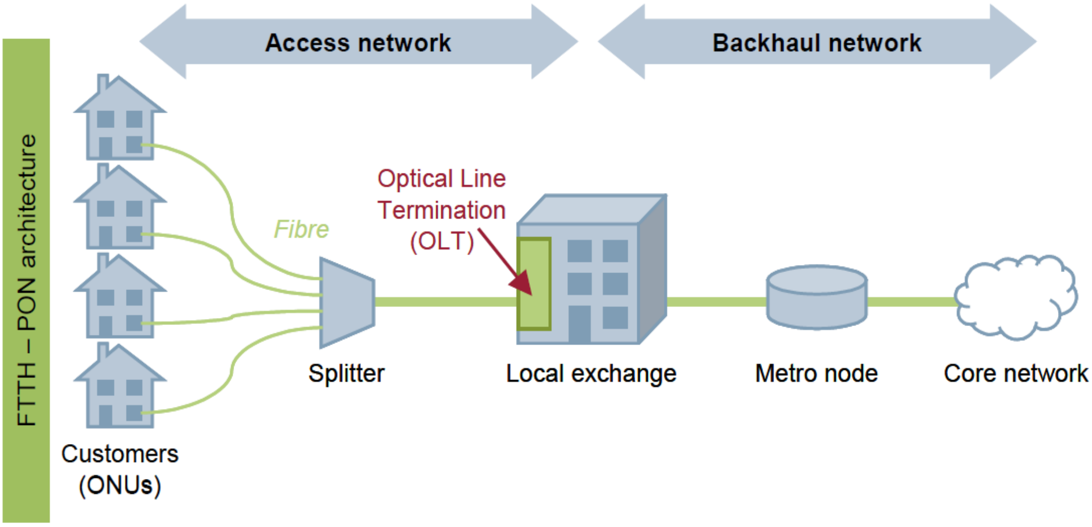


Figure 3: FTTH - PON architecture [3]

As this project is being developed in a European context and the EPON networks are mostly used in Asia, the basis for this work will be the GPON and as such the EPON network will be described in lesser detail when compared with GPON.

Based on GPON, the next generation XG-PON with increased transmission rates already had some field trials and is a possible solution for increased needs in bandwidth.

2.1 GPON

Figure 4 and Figure 5 illustrate how a GPON network works. The downlink signal is sent to all subscribers at 1490 nm wavelength and is then filtered by each user. An alternative 1550 nm wavelength can be used for analog television transmission and other services.

The uplink signal uses the 1310 nm wavelength shared by all users by assigning different time slots to each one.

The wavelength values described are the ones commonly used, however, on the G.984.2 standard a wavelength range for each transmission is defined as follows [35]:

Downstream – 1480 nm to 1500 nm
Upstream – 1260 nm to 1360 nm
Video – 1550 nm to 1560 nm

The transmission rates of 2.5Gbit/s for downstream and 1.2Gbit/s for upstream are not the only possible implementations of a GPON network but are the most commonly used.

The line code used in both transmission directions is the NRZ (Non-Return-to-Zero) as defined in the G.984.2 standard [35]. The convention used, is for a high level of light emission to indicate a binary one and a low level light emission for a binary zero.

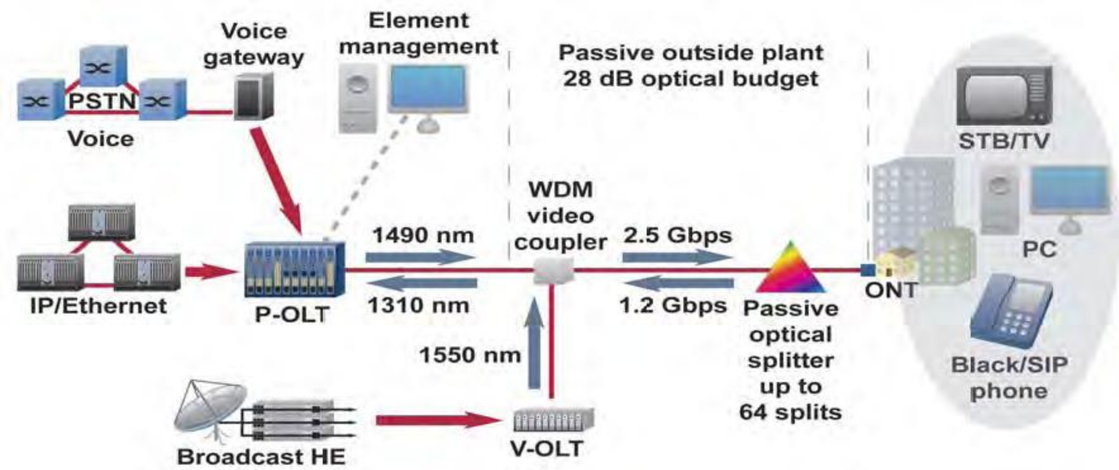


Figure 4: Schematic diagram of a GPON network [4]

With a 28 dB optical budget the network can only get to 20 km, however by reducing the splitting factor to a maximum of 1:16 the range can be extended up to 30 km. These values are due to the physical layer limitations, as the maximum logical reach is 60 km.

The maximum split ratio with the above mentioned characteristics is 1:64, however with the available technology it is possible to go up to 1:128 splitting factor using a higher optical power budget.

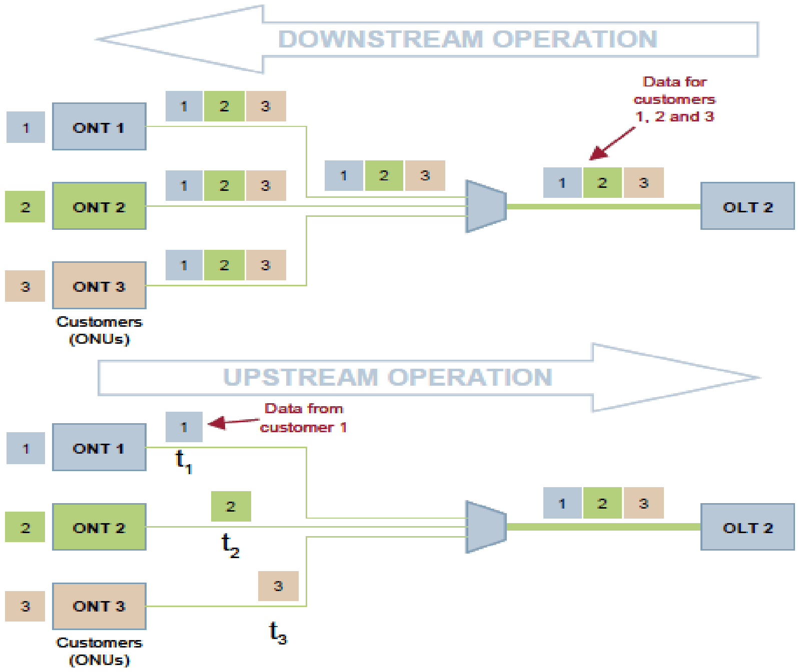


Figure 5: Functional diagram of downstream and upstream GPON system [3]

Unlike the previous PON networks which used the ATM protocol, GPON uses GEM (GPON Encapsulation Method) to provide all types of services like ATM, Ethernet and TDM [5].

The information is transmitted with a frame format called GTC as shown in Figure 6. The downstream frame consists of the PCBd (Physical Control Block downstream) and the GTC (GPON Transmission Convergence) payload. The upstream frame is comprised by the PLOu (Physical Layer Overhead upstream) and bandwidth allocation intervals associated with each ONU.

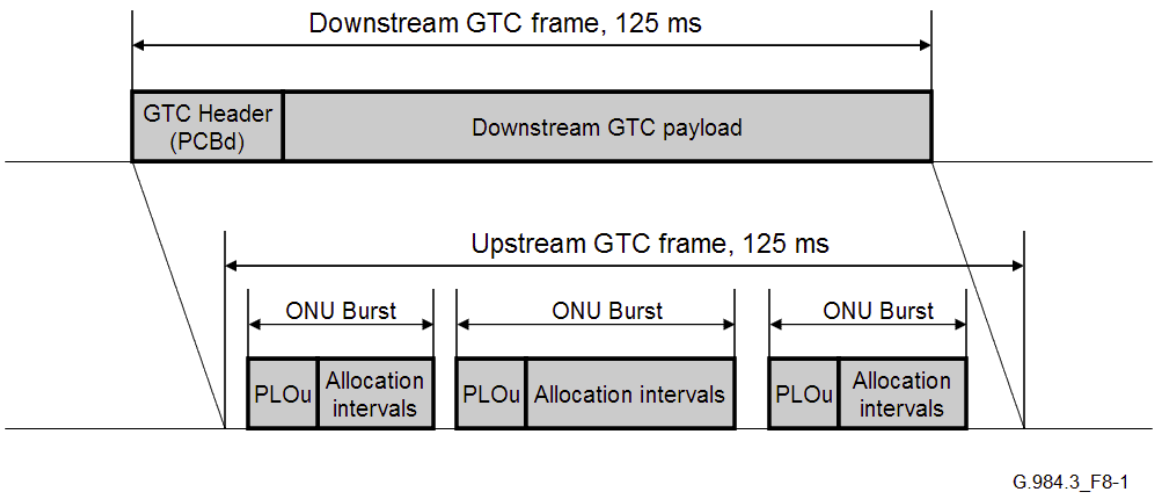


Figure 6: GTC layer framing [5]

As the downstream frame has duration of 125 ms and is 38880 bytes long the resulting 2.5 Gbit/s data rate is achieved. The PCBd length range depends on the number of allocation structures per frame.

Figure 7 shows the GTC downstream frame

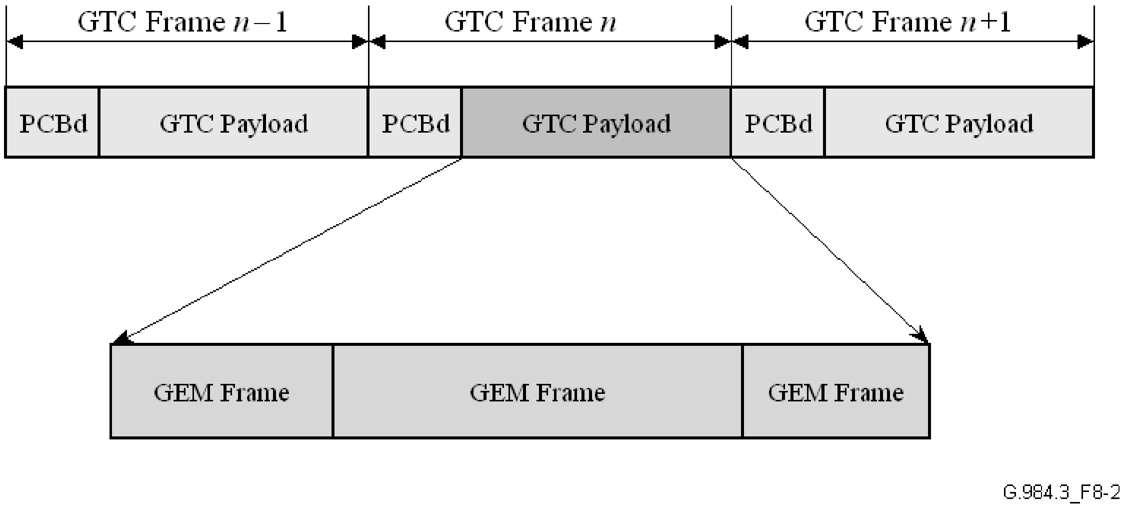


Figure 7: GTC downstream frame [5]

As noted before, the GPON typical use is in a FTTH network however there are other possible implementations. Figure 8 shows some of them:

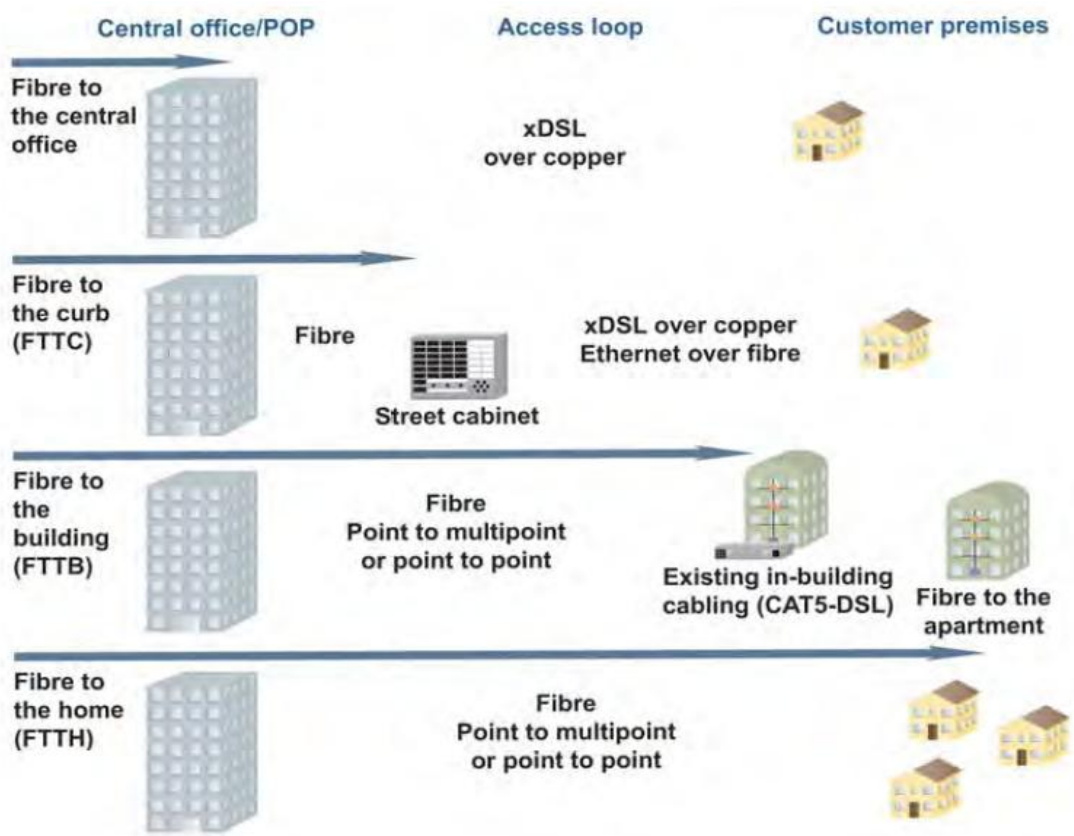


Figure 8: Different types of FTTx (Fiber-to-the-x) networks [4]

These several possible network solutions are dependent on the position of the ONU, for example in a FTTC (Fiber-to-the-Curb) network, there is a fiber connection to a cabinet usually in an adjacent street to the building where the users are and then the rest of the network is done using copper cable. The other options use similar solutions where there is a fiber connection to the ONU and then a copper connection to the end user.

The FTTH network is the preferred implementation as there is no need for an active piece of equipment between the central office and the end user however the other options are still commonly used as the copper infrastructure is already present the cost of implementing it is lower.

With the release of the G.984.5 standard [12], the wavelength range of the GPON signals is redefined to enable the coexistence of GPON with additional services such as NGA (Next Generation Access) and video.

The new wavelength range for the downstream signal is called the "basic band" while the band reserved for additional services is called the "enhancement band". To prevent signal degradation by having interference between the two signals a "guard band" is defined to separate them. The necessary isolation outside the "guard band" is achieved by using WBFs (Wavelength Blocking Filters) [12].

Figure 9 defines the wavelength allocation plan including the wavelength bands reserved for additional services.

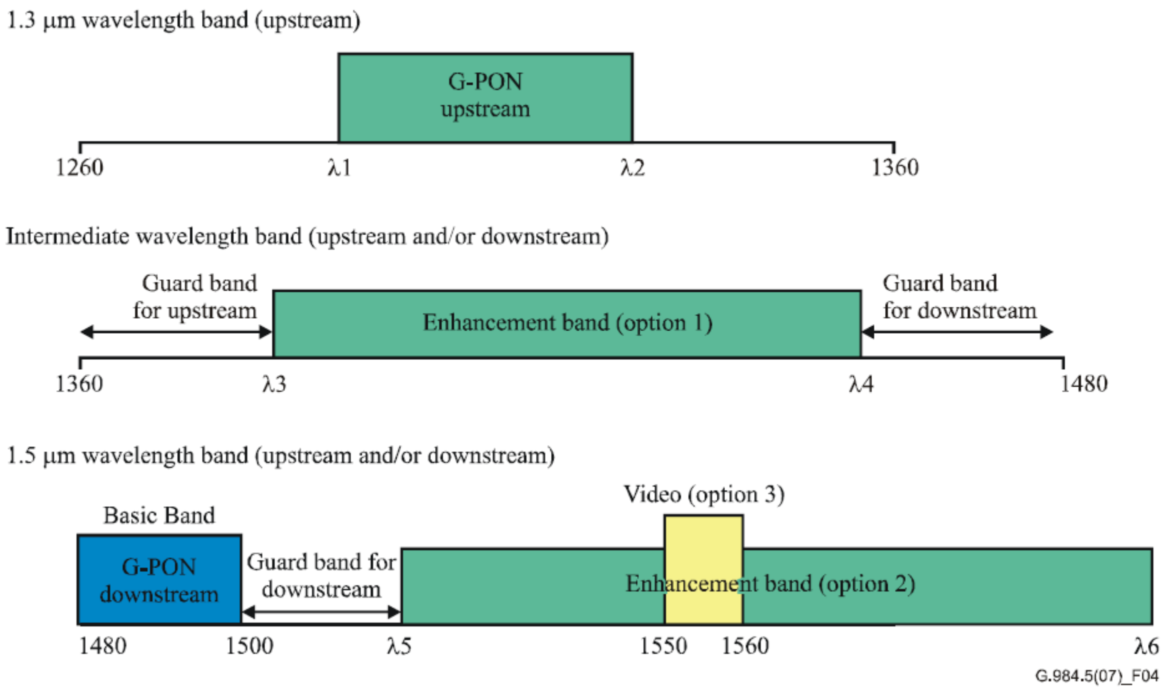


Figure 9: Wavelength Allocation GPON [12]

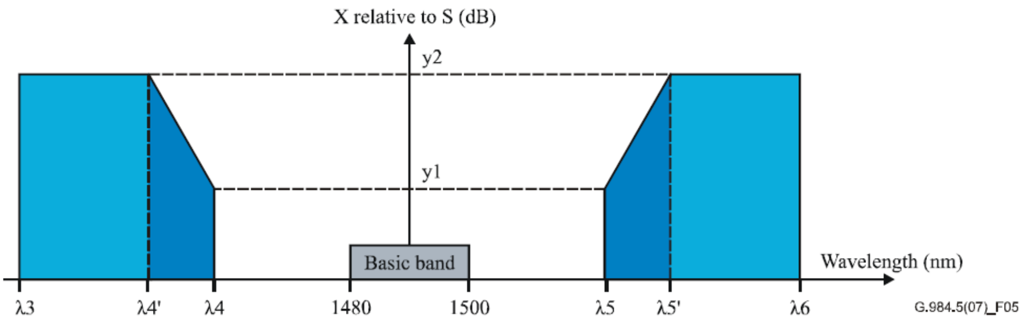
Table 1 shows a possible wavelength range for these bands using low cost WBFs.

Items	Notation	Unit	Nominal value	Application examples
1.3 µm wavelength band				For use in G-PON upstream.
– Regular wavelength band option				e.g., ONUs based on Fabry-Perot lasers.
Lower limit	λ1	nm	1260	
Upper limit	λ2	nm	1360	
– Reduced wavelength band option				e.g., ONUs based on ordinary DFB lasers.
Lower limit	λ1	nm	1290	
Upper limit	λ2	nm	1330	
– Narrow wavelength band option				e.g., ONUs based on wavelength selected lasers.
Lower limit	λ1	nm	1300	
Upper limit	λ2	nm	1320	
Enhancement band (option 1-1)				For next generation access (NGA).
Lower limit	λ3	nm	1415 *(Informative)*	NOTE – The values are informative. The loss in this band is not guaranteed in optical branching components for PON (i.e., power splitters) specified in G.671 nor in optical fibres specified as G.652A&B (non-low-water-peak fibres).
Upper limit	λ4	nm	1450 *(Informative)*	
Enhancement band (option 1-2)				For next generation access (NGA).
Lower limit	λ3	nm	1400 *(Informative)*	Applicable for low-water-peak fibre only. NOTE – The values are informative. The loss in this band is not guaranteed in optical branching components for PON (i.e., power splitters) specified in G.671.
Upper limit	λ4	nm	1450 *(Informative)*	
Items	**Notation**	**Unit**	**Nominal value**	**Application examples**
Basic band				For use in G-PON downstream.
Lower limit	–	nm	1480	
Upper limit	–	nm	1500	
Enhancement band (option 2)				For next generation access (NGA).
Lower limit	λ5	nm	1530	NOTE – The upper-limit value is determined as an operator choice from 1580 to 1625 nm considering the following factors.
Upper limit	λ6	nm	1580 to 1625	– Bending loss of optical fibre that increases at longer wavelengths. – Loss of a filter that separates/combines a monitoring signal and NGA signal(s) (if an optical monitoring system is used).
Enhancement band (option 3)				For video distribution service.
Lower limit	–	nm	1550	
Upper limit	–	nm	1560	
NOTE – Additional guard bands are needed in the case of the coexistence of option 2 and option 3 (see Appendix II).				

Table 1: Parameters for Wavelength allocation GPON [12]

Knowing that the usual wavelengths used in a GPON network are 1310 nm for upstream and 1490 nm for downstream transmission, it is relevant to point out that for example, the upstream preferred wavelength is compatible with DFB and Fabry-Perot lasers. As such it is important to note that the wavelengths commonly used are due to the need to implement several services in a GPON network. As such the value used is usually the middle value on the possible wavelength range.

In order to minimize the effect of interference signals the ONUs need a way to isolate these signals using a WBF and WDM filter. The isolation characteristics of these filters are not specified in the standard but the X/S (S is the optical power of the basic band signal and X is that of the interference signal(s)) tolerance of the ONUs is defined [12].



Wavelength (nm)	λ3	λ4'	λ4	λ5	λ5'	λ6
	1415/1400 *(Informative)*	1441 *(Informative)*	1450 *(Informative)*	1530	1539	1580 to 1625
X relative to S (dB)	y2	y2	y1	y1	y2	y2
	22 *(Informative)*	22 *(Informative)*	7 *(Informative)*	7	22	22

S Received power of basic band.
X Maximum total power of NGA and video received in the blocking wavelength range.
X/S in the mask (hatching area) should not cause the sensitivity of the basic band receiver to fail to meet the specified limit.
NOTE – λ3 value of 1400 *(Informative)* may be applicable for low-water-peak fibre only.

Figure 10: X/S Tolerance mask for ONU [12]

Figure 10 shows the X/S tolerance mask which should not cause the sensitivity of the basic band receiver to fail to meet the specified limit. [12]

The format for the interference signal used in measuring the X/S tolerance should be NRZ pseudo-random coded using the same or lower bit rate as the downstream signal.

2.2 EPON

EPON is based on the IEEE 802.3 standard and, as such, Ethernet traffic is transported natively, and its features are fully supported, unlike GPON, where the Ethernet services are adapted at the OLT and ONU.

As both PON protocols are an evolution of the G.983 standard defined for BPON, most of their main concepts are the same, as shown in Table 2:

Type		Broadband PON (BPON)				GPON (Gigabit-Capable PON): GPON		GPON (Gigabit-Capable PON): GPON-ERG		EPON (Ethernet PON)	
Standard		ITU-T G.983 series				G.984 series		G.984.6		IEEE 802.3ah	
Protocol		ATM				Ethernet, TDM, TDMA				Ethernet	
Services		Voice, data, video				- Voice, data - Triple-play - File exchange, remote learning, tele-medecine, IPTV, video-on-demand				Triple-play	
Maximum physical distance (OLT to ONT)	km	20				20		Up to 60 (ODN distance)		1000BASE-PX10: 10 1000BASE-PX20: 20	
Split ratio		up to 32				up to 64		16, 32 or 64 (restricted by path loss)		1x16 1x32 (with FEC or DFB / APD)	
		Downstream OLT Tx		Upstream ONU Tx		Downstream	Upstream	Downstream	Upstream	Downstream	Upstream
Nominal bit rate	Mbit/s	155.52 622.08	1244.16	155.52	622.08	1244.16 / 2488.32	155.52/622.08/ 1244.16	2488.32	1244.16	1000	1000
Operating wavelength band	nm	1480-1580	1480-1500	1260-1360	1260-1360 (MLM1, SLM) 1280-1350 (MLM2) 1288-1338 (MLM3)	-1480-1500 -1550-1560 (Enhancement band for video)	1260-1360 Possibility of using shorter C-band wavelengths downstream and 1550 nm upstream	1480-1500 (Basic band) 1550-1560 Enhancement band- for video distribution	OEO (ONU EXT): 1260-1360 OEO (OLT EXT): 1290-1330 OA: 1300-1320 (OBF)	100BASE-PX10: Downstream: 1490 nm + PIN Rx Upstream: 1300 nm (low-cost FP optics + PIN Rx) 100BASE-PX20: Downstream: 1490 nm + APD Rx Upstream:1300nm (DFB optics + PIN Rx)	
ORL_{MAX}	dB	>32				>32				15	

Table 2: PON technologies comparison [30]

Even though the wavelengths used for signal transmission are the same there are some important differences between EPON and GPON. As explained above, Ethernet traffic is transported natively in an EPON network and so there is no need for changes in the framing when transmitting this type of protocol.

Figure 11, shows the difference in framing between both technologies.

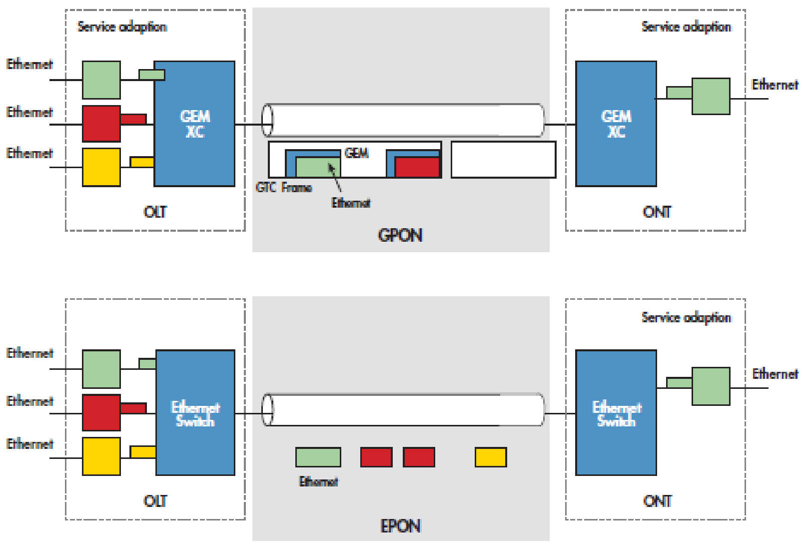


Figure 11: Framing in GPON and EPON [31]

As most of the different concepts in an EPON network are in terms of framing which is not relevant for the purpose of this dissertation, the main points important to note are that in terms of signal transmission the concept is the same.

In terms of downstream transmission the OLT broadcasts the information to all ONUs and each one knows which information is destined to it by the frames received. This is shown in Figure 12.

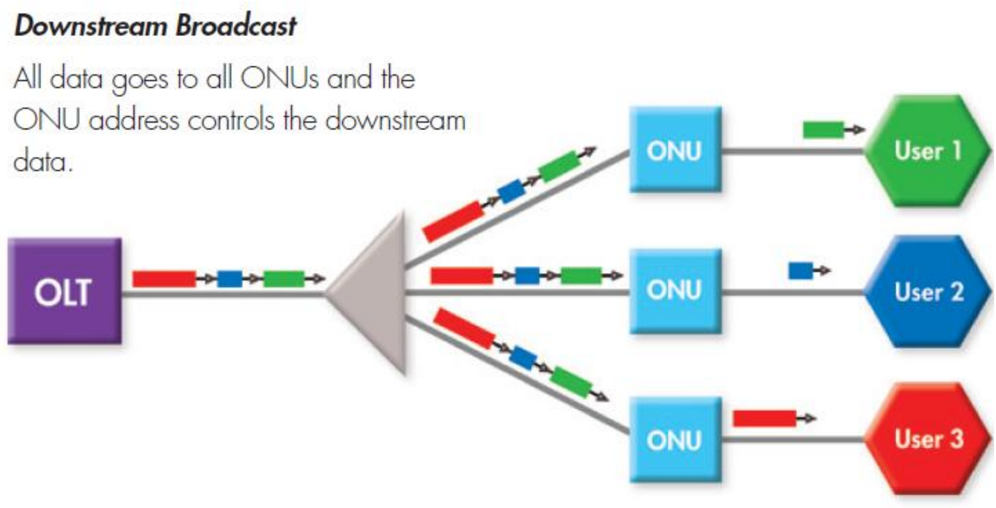


Figure 12: EPON Downstream [31]

In terms of upstream transmission, it is done in the same manner as for a GPON network. Each ONU has a designed time slot for its transmission using TDMA.

Figure 13 demonstrates how the upstream transmission works.

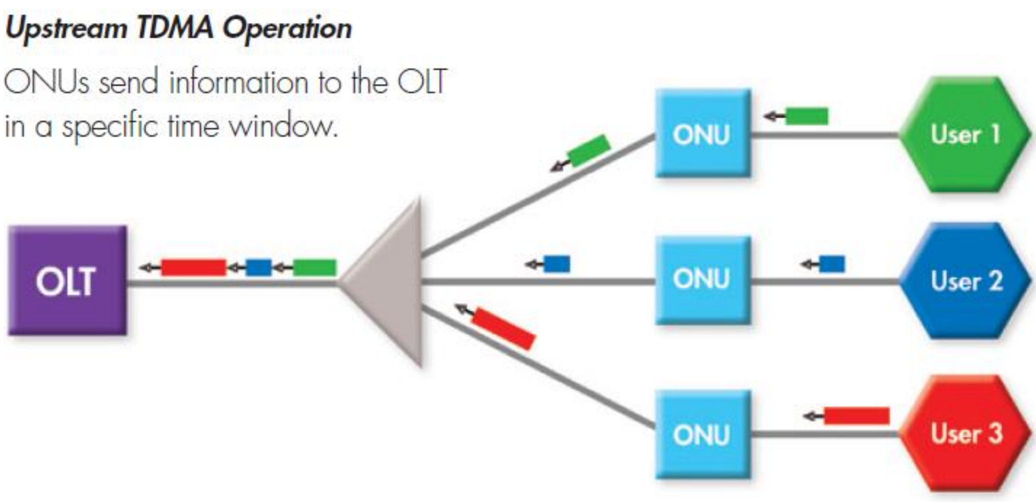


Figure 13: EPON Upstream [31]

An important clarification to note however is that even though the transmission method is similar to the GPON network, the information being transmitted is quite different and as such, both networks cannot coexist in the same system.

2.3 XG-PON

XG-PON also called 10GPON is the next step for GPON networks. Not only are the data rates increased up to four times but it is also compatible with existent networks since it uses a different wavelength both for downstream and upstream transmission. As shown in Figure 14, by using a WDM multiplexer a normal GPON signal can be joined with a 10GPON signal in the same fiber [10].

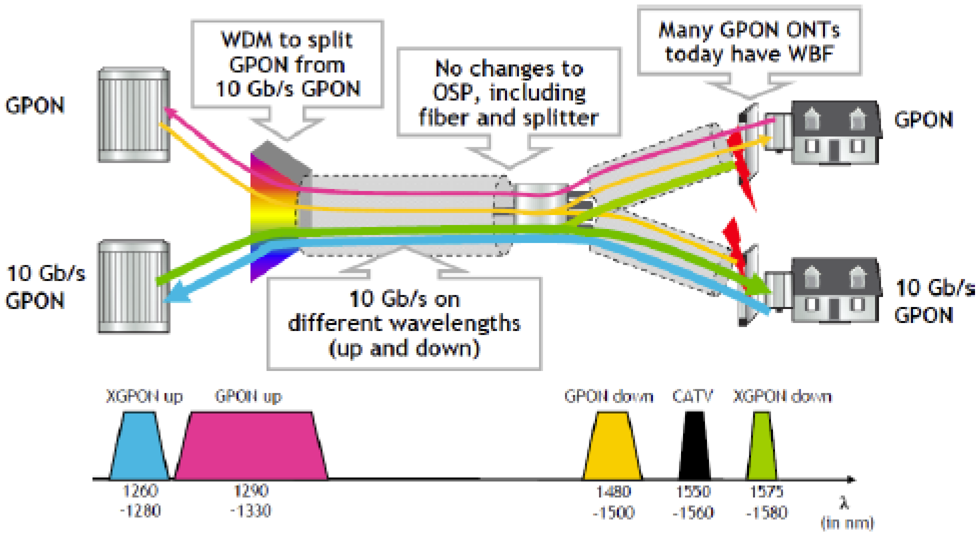


Figure 14: Co-existence of GPON and 10GPON in the same infrastructure [10]

There are two types of XG-PON, the XG-PON1 is asymmetric and uses 10 Gbit/s data rate for downstream and 2.5 Gbit/s upstream while XG-PON2 is symmetric with 10 Gbit/s.

In the first standard defined for XG-PON (G.987.1) [13], only the first case is defined as the later would require more expensive burst-mode lasers on ONTs to deliver the upstream transmission speed.

Another advantage of this technology to existing PON networks is the added range, now possible to reach up to 60 km and the capability of a splitting factor up to 1:256 [13].

In terms of line code for the transmission, NRZ is once again used [13].

The standard also defines a wavelength allocation plan to enable coexistence of XG-PON with additional services. The purpose of this plan is the same as mentioned for GPON where there are several bands defined for each wavelength range so that interference between signals is minimized. The values for these ranges are defined in Figure 15 and Table 3 [13].

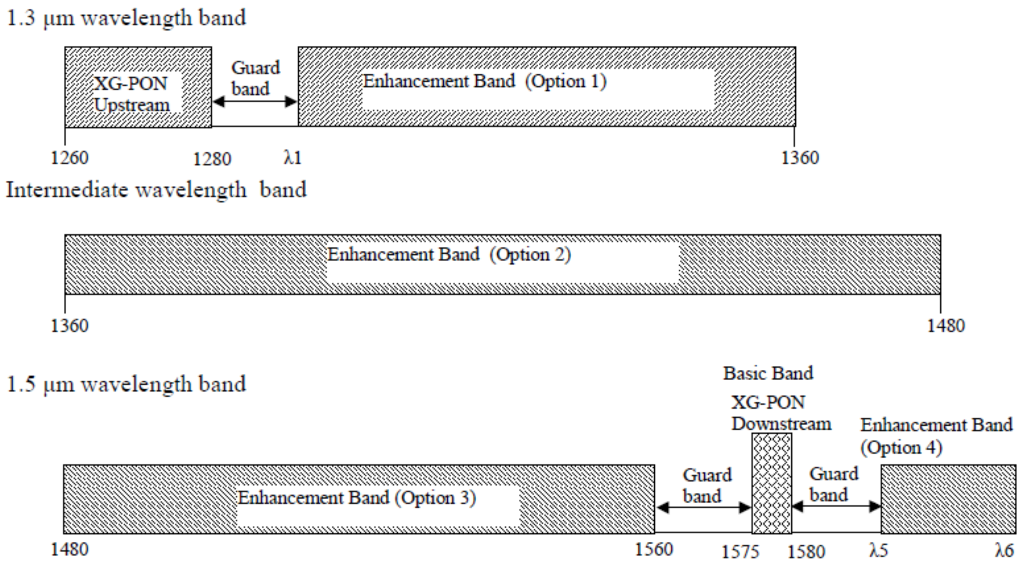


Figure 15: Wavelength Allocation XG-PON [13]

Important information to gather from Figure 15 is the wavelength ranges used when compared to a GPON network. In order for this technology to coexist with current networks it was paramount for the wavelengths available for transmission to be outside the values possible in a normal GPON network. As such, the wavelength range for upstream is between 1260 and 1280 nm while for downstream it is between 1575 and 1580 nm.

Table 3 describes these values and points out that the GPON wavelength ranges are in this case considered enhancement bands.

Items	Notation	Unit	Nominal value	Application examples
XG-PON1 Upstream				For use in XG-PON1 upstream.
Lower limit	–	nm	1260	
Upper limit	–	nm	1280	
Enhancement band (option 1)				For use in G-PON upstream (Reduced option: 1290-1330 nm).
Lower limit	λ1	nm	1290	
Upper limit	–	nm	1330	
Enhancement band (option 2)				For future use. NOTE – The values are informative. The loss in this band is not guaranteed in optical branching components for PON (i.e., power splitters) specified in [b-ITU-T G.671] nor in optical fibres specified as ITU-T G.652 A&B (non-low-water-peak fibres).
Lower limit	–	nm	1360 *(Informative)*	
Upper limit	–	nm	1480 *(Informative)*	
Enhancement band (option 3)				For use in G-PON downstream (1480-1500 nm) and/or video distribution service (1550-1560 nm).
Lower limit	–	nm	1480	
Upper limit	–	nm	1560	
XG-PON downstream (Basic band)				For use in XG-PON1 downstream (Note 2)
Lower limit	–	nm	1575	
Upper limit	–	nm	1580	
Items	**Notation**	**Unit**	**Nominal value**	**Application examples**
Enhancement band (Option 4)				For future use. NOTE – The upper-limit value is determined as an operator choice from TBD (to be determined) to 1625 nm, considering the following factors: bending loss of optical fibre that increases at longer wavelengths; loss of a filter that separates/combines a monitoring signal and user signal(s) (if an optical monitoring system is used)
Lower limit	λ5	nm	TBD	
Upper limit	λ6	nm	TBD to 1625	
NOTE 1 – Proper guard bands should be considered in the case of multiple wavelengths in the same Enhancement band. NOTE 2 – Enhanced wavelength band of 1575-1581 nm is allowed in the case of outdoor OLT operations.				

Table 3: Parameters for Wavelength allocation XG-PON [13]

In terms of frame format it is similar to a GPON network where the frame consists of a header and the payload. For the downstream transmission with a frame length of 155520 bytes and 125 µs duration the 10 Gbit/s data rate is achieved.

Figure 16 shows the XG-PON downstream frame in order to compare it with the GPON frame presented in Figure 7.

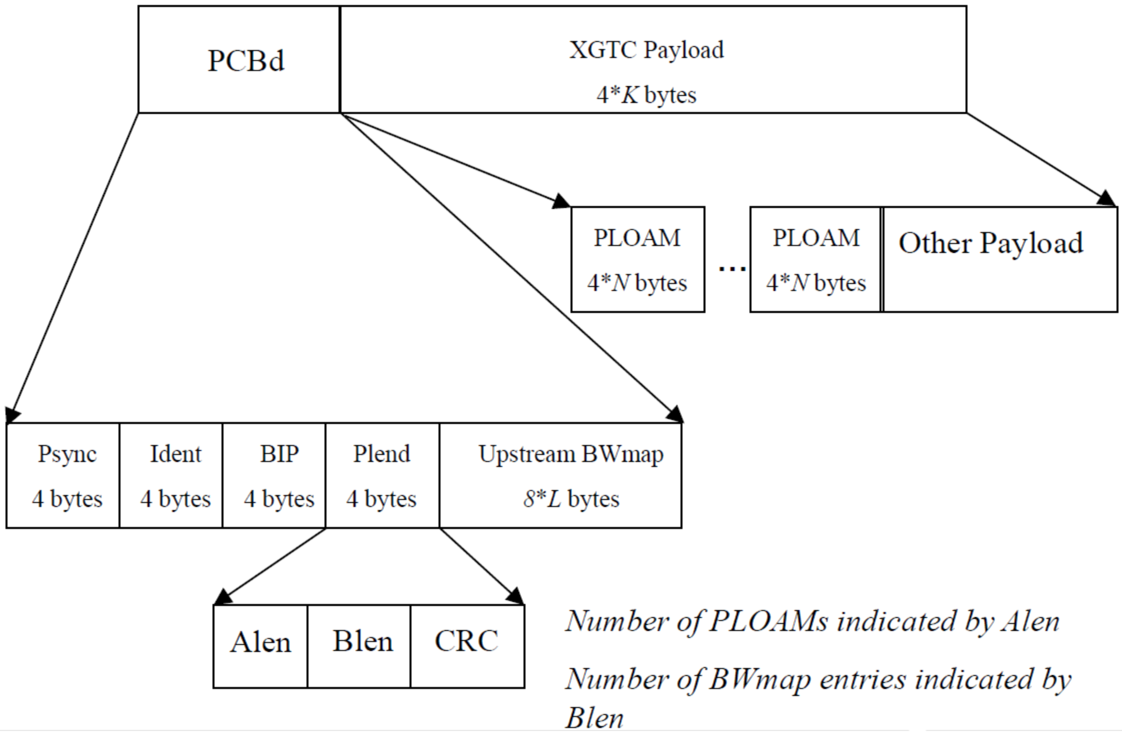


Figure 16: XG-PON downstream frame [8]

Even though the XG-PON was an important step forward in accompanying the increased needs for higher bandwidth, there are still improvements to be made.

XG-PON was labeled NGPON1 (Next-Generation Passive Optical Network) as the first phase of the next generation of PON networks.

2.4 NGPON2

There are several contenders for the next leap in network technology due to the fact that several of these advancements require a massive investment from the operators in order to implement the required equipment.

In the next sub-chapters the advantages and inconveniences of these options will be discussed, showcasing the reasons some of them are not feasible with current networks even though the benefits in terms of bandwidth would be significant.

Since a standard for NGPON2 is still in preparation, it is important to highlight the main features of each technology in order to deduce which option is further ahead in development and the reasons that might lead to its implementation in the near future. Even though, some of these might never leave an experimental phase it is always important to find the reasons for it, either economic or technical. Some of the possible solutions are: WDM-PON, ODSM-PON, Stacked XG-PON, TWDM-PON and OFDM-PON.

Figure 17 shows a comparison of how much it costs for an operator to offer different network services:

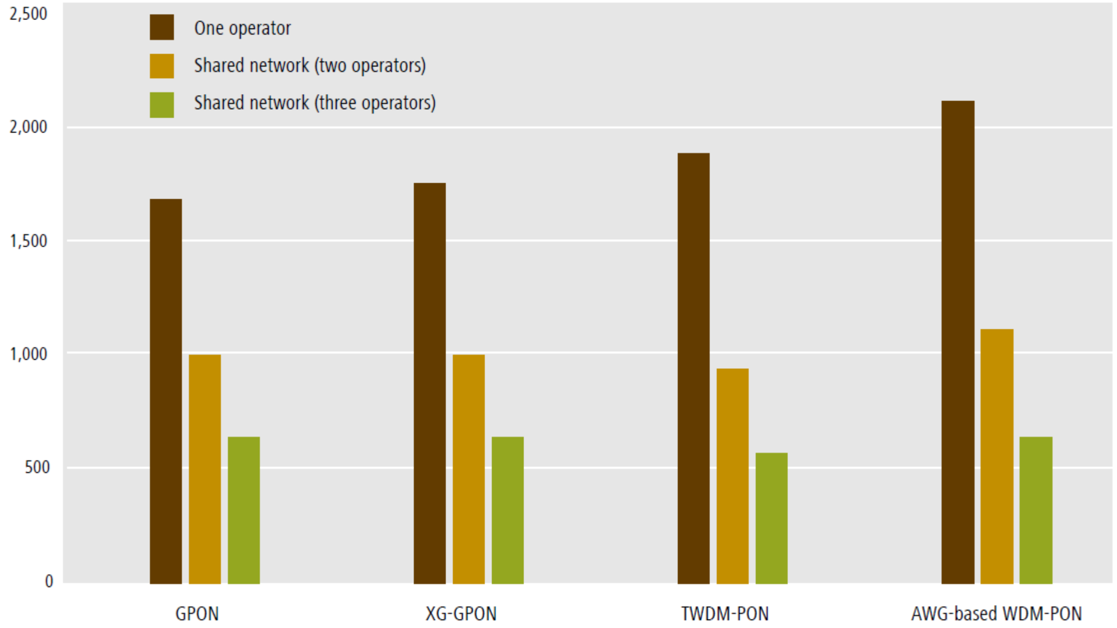


Figure 17: Cost per home connected (USD), 50% market share overall, urban deployment [17]

As shown, the cost of maintaining an NGPON2 network is similar to the currently available solutions and, as such, an option to implement these solutions at a reasonable cost is one of the main setbacks in introducing these technologies.

2.4.1 WDM-PON

A typical WDM-PON solution is presented in Figure 18:

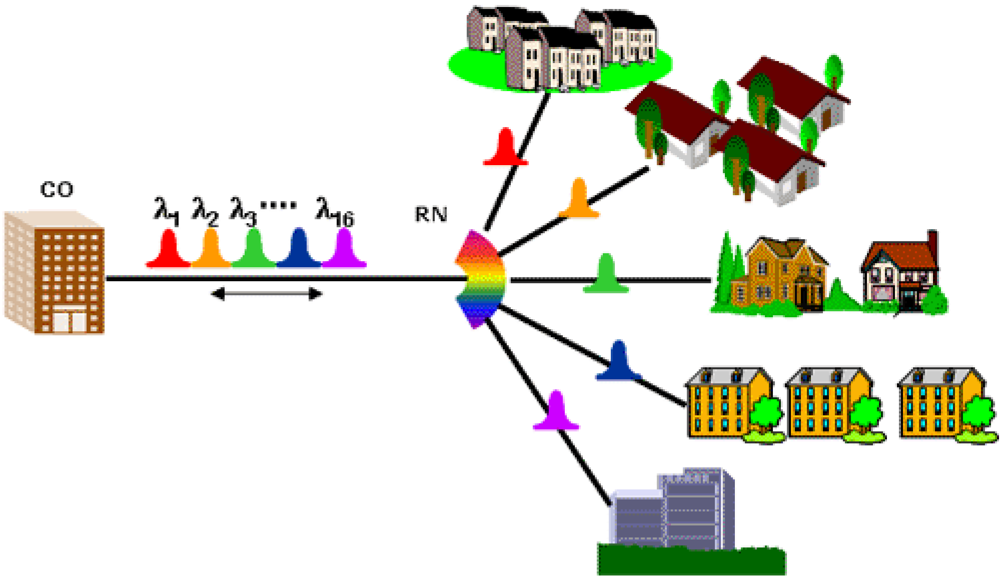


Figure 18: Typical WDM-PON system [36]

As shown in the figure, the network architecture for a WDM-PON solution is similar to the TDM-PON solutions present in the market and described in the previous chapters. The main difference however is that instead of assigning different time slots to each user, in this case there is a specific wavelength for each subscriber. As such a WDM-PON network can be described as an aggregation of point-to-point connections between each user and the central office. [36]

As each ONU is tuned to a specific wavelength this represents several challenges in terms of developing a viable solution to implement such a complex network. Since these components are sensitive to temperature variations and using a different wavelength to each ONU requires a DWDM (Dense Wavelength Division Multiplexing) solution, there is a need for this equipment to be as immune to small variations in the spectrum as possible. [7]

The two main challenges that should be overcome to implement a feasible WDM-PON are the following:

Challenge 1: Addressing the real-time consistency between the wavelength of optical transceivers and the connecting AWG port. [7]

To solve this issue colorless optical source technology is used. Several studies have been conducted in order to find the best solution, for example in the paper [14] by using bidirectional colorless transceivers it is possible to implement a low cost (compared to some of the options) option which helps solve this issue.

Challenge 2: Addressing the real-time consistency between the wavelengths of the port on the local AWG (at the CO (Central Office)) and the port on the remote AWG. [7]

Using wavelength alignment technology this challenge can be overcome with optical power monitoring and temperature insensitive AWGs. As mentioned above small variances in the spectrum can result in signal loss so having equipment immune to temperature is a necessity. [7]

Even though most of the major challenges present in implementing this solution are already overcome and its benefits are substantial it is still not planned to implement this type of network in a large scale due to the need to reshape current networks and most importantly the lack of an international standard to define the characteristics each operator should implement in their network.

Some field trials were already done using WDM-PON in Korea with positive results however a full implementation of these types of networks is still in the future, as a standard is yet to be released by ITU-T.

	IS-WDM PON		Remodulated IS-WDM PON	TL-WDM PON
Data rate/ λ	125 Mb/s	1.25 Gb/s	1.25 Gb/s	1.25 Gb/s
WDM channels	32	16	16	16
Channel spacing	100 GHz	200 GHz	200 GHz	100 GHz
Transmission length	40 km	20 km	20 km	> 20 km
Fiber loss	12 dB	< 10 dB	< 10 dB	< 25 dB
RN Operating temp.	-40 °C ~ +65 °C	-40 °C ~ +65 °C	-40 °C ~ +65 °C	-40 °C ~ +65 °C
	Commercialized	In Pilot	In Pilot	In Labs

Table 4: WDM-PON status in South-Korea [11]

2.4.1.1 WDM-PON Technologies

In this sub-chapter several examples of possible implementations for a WDM-PON technology will be compared based on a Huawei Technologies document [18].

By showing the possible solutions with its main advantages and disadvantages it is possible to perceive the best option to implement in a WDM-PON in a practical sense.

In order demonstrate the difference between all the options available, and facilitate a comparison between them Table 5 describes the main characteristics of all these technologies:

Scheme	Bit rate/channel	No. channels	Pros	Cons
Spectrum slicing: LED	Low, <155 Mb/s	Low, ≤16	Very cheap No seed needed	Poor scalability and reach
Spectrum slicing: SLED/SOA	Low, <155 Mb/s	Medium, ~32	Inexpensive No seed needed	Low bit rate and short reach
Injection locked FP with ASE injection	Low, ~1.25Gb/s	Medium, ~32	Inexpensive	Non-standard FP needed (wide gain spectrum) RIN limits bit rate and transmission distance
Injection locked FP with laser injection	Medium, >2.5Gb/s	Medium, ~32	Inexpensive	Non-standard FP needed (wide gain spectrum) Polarization dependent upon injection
Injection locked FP with self-seeding	Medium, >1.25Gb/s	Medium, ~32	Inexpensive No seed needed	Non-standard FP needed (wide gain spectrum) Polarization dependent upon injection
RSOA: with ASE injection	Medium, <5 Gbit/s	Medium, ~32	Relatively high bit rate	Relatively expensive, Seed source needed Chromatic dispersion limited
RSOA: laser array seeding	Medium, <5 Gbit/s	High, >32	Relatively high bit rate	Laser bank seed source needed Polarization dependent, backscattering problem
RSOA with re-modulation	Medium, <5 Gbit/s	High, >32	Relatively high bit rate No seed source	Downstream extinction ratio is limited Backscattering affects upstream performance
REAM	High, >10 Gbit/s	Low, <32	High bit rate	Expensive; Relatively high injection power Backscatter affects upstream performance
Tuneable laser	High, ≥10Gbit/s	High, ≥ 32	Good output power => long reach No seed needed Wavelength flexible	Expensive External modulator needed Wavelength assignment algorithm needed

Table 5: Comparison of Colorless Lightsources [18]

As expected when comparing the available technologies together, the most economical solutions are also the least effective, having short reach, low bit rate and several other disadvantages. The tunable lasers approach presents itself as the best option as even with its high cost associated it offers the best performance. As such further on this dissertation (chapter 3) this solution will be the one analyzed in greater detail.

2.4.2 ODSM-PON

The ODSM-PON (Opportunistic and dynamic spectrum management PON) solution, first proposed several years ago is one of the preferred options for network operators as it keeps the ONU and OLT untouched. By enabling a better service for clients without having to change the available infrastructure it is possible to offer this service at an affordable cost. As shown in Figure 19 the only changes needed are in the CO where the old cards delivering GPON or XG-PON are replaced by a WDM splitter and a new CO is built to support the transmission. [7]

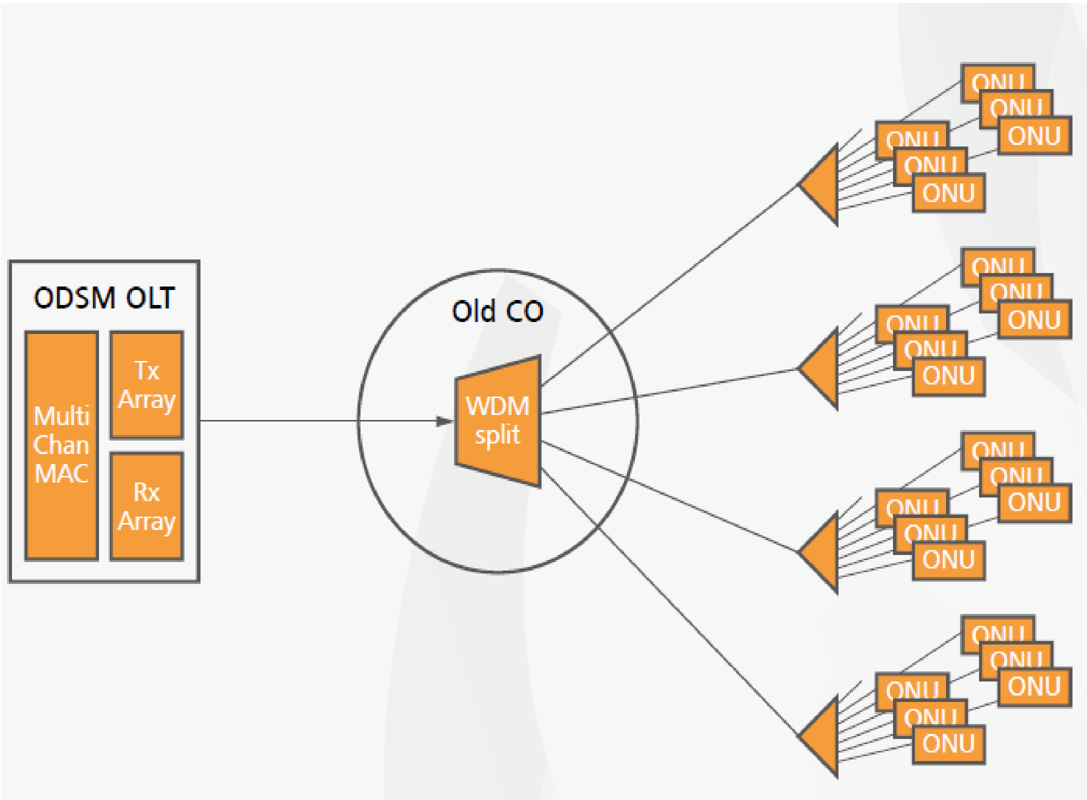


Figure 19: ODSM PON [7]

The downstream transmission is done using the WDM splitter where all the wavelengths are sent in the same fiber and then distributed to each to the respective ONUs. The upstream transmission however uses a dynamic TDMA+WDMA solution where the respective transmissions of each ONU are combined in the WDM splitter and then transmitted to the OLT [7].

The main ODSM-PON features are the following: [7]

- Leverages the existing ODN from the CO to user premises.
- Leverages the existing ONU at user premises.
- Cost reduction and power saving with the passive “Old CO”.
- Substantially improves (by 10-fold) the fiber sharing between the CO and metro devices.
- Follows GPON/XG-PON1 deployment policies by allowing for an upgrade as required mode.

2.4.3 *Stacked XG-PON*

As described in the XG-PON chapter this implementation is possible when for example a 10GPON and a GPON signal are both transmitted in the same fiber at different wavelengths as shown in Figure 20.

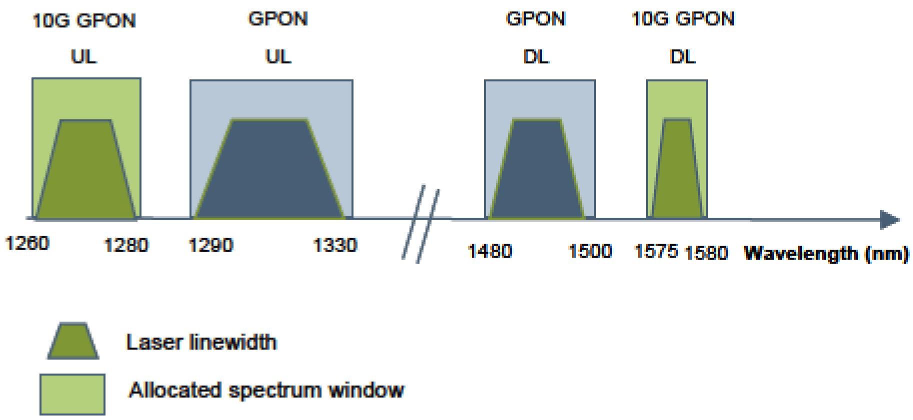


Figure 20: TDM PON allocated spectrum vs. laser linewidth [3]

The main purpose of this solution however is the possibility of multiplexing several 10GPON networks on the same fiber as it would be possible to use CWDM (Coarse Wavelength Division Multiplexing), a less expensive option then the one needed for WDM-PON. This implementation is demonstrated on Figure 21.

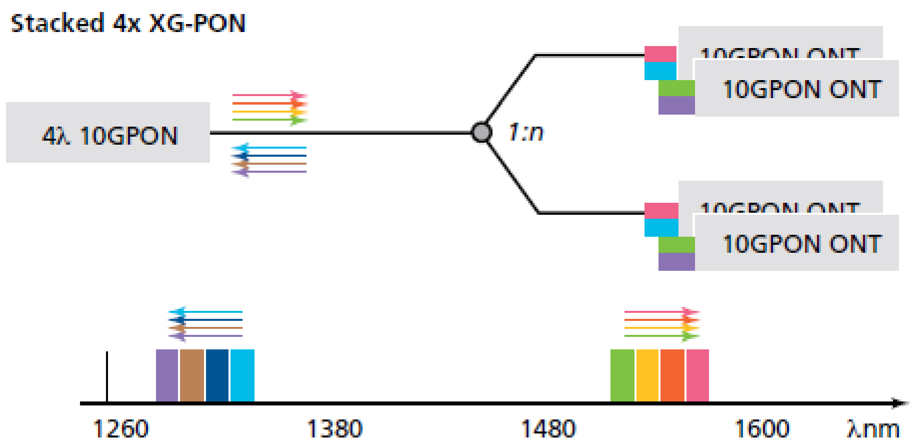


Figure 21: Stacked 4x XG-PON [10]

The key to this solution is wavelength planning as the available ONUs will need to be changed to colored ones. This option not only has the advantage of increased bandwidth but also offers the possibility of leasing specific wavelengths to different operators in the same way as it is done with fiber nowadays. Several operators can use the same infrastructure with only the need for a specific wavelength centered ONT (Optical Network Terminal).

2.4.4 TWDM-PON

TWDM-PON (Time and Wavelength Division Multiplexed PON) is a hybrid system where in a single fiber 4 XG-PON are joined to have a 40 Gbit/s downstream capacity. This technology is considered by FSAN to be the best option for NG-PON2 due to being considered the less risky and expensive solution for network operators. Not only is the transmission rate increased by 4 times both downstream and upstream but there are also other significant advantages, the ODN (Optical Distribution Network) from available networks can be reused allowing for coexistence with available solutions and the ONU is colorless and reconfigurable.

TWDM-PON considered as the best option for next generation networks it is now one step closer to a standard being developed. One of the first challenges in standardizing this solution is defining the wavelengths available for its use, Figure 22 shows the wavelengths used in current solutions.

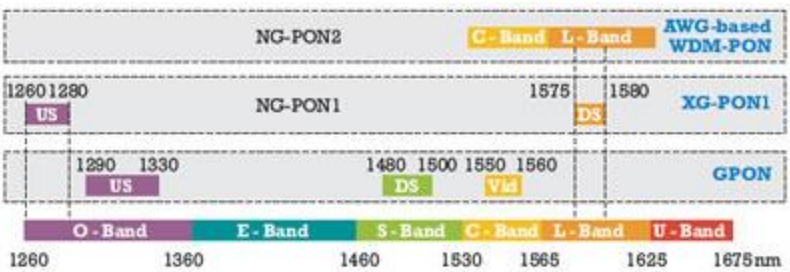


Figure 22: PON Wavelength plan [15]

As described in the GPON and XG-PON chapters there are wavelengths bands which are not used to limit interference between signals, since for a TWDM-PON solution there is a need for a higher wavelength band to transmit the various XG-PON signals one of the problems will be in defining the wavelengths that can be used without interfering with available networks.

There are two options to for a wavelength plan that can be used for TWDM-PON, Figure 23 shows a possible solution based on the C-band while Figure 24 shows an implementation using the XG-PON wavelength plan. [16]

Option 1: C-band Wavelength plan

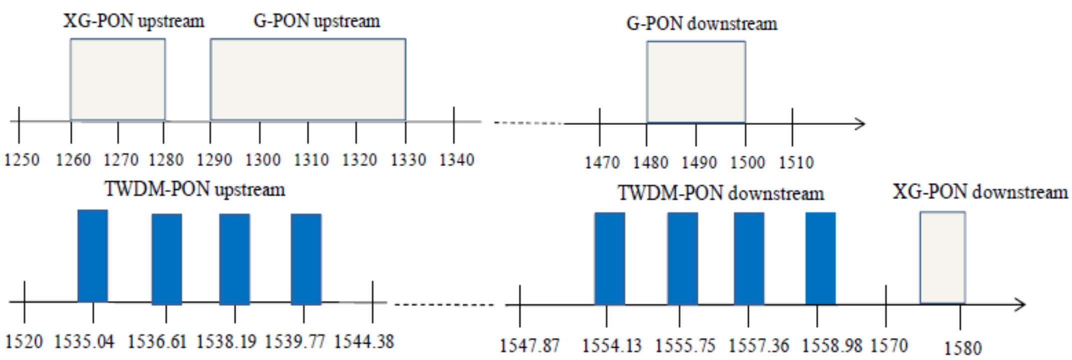


Figure 23: C-band Wavelength plan [16]

Using this option, both upstream and downstream transmissions are done on the C-band (1530 to 1565 nm) which as shown, is between the GPON downstream wavelength range and the XG-PON downstream.

Option 2: XG-PON Wavelength reuse

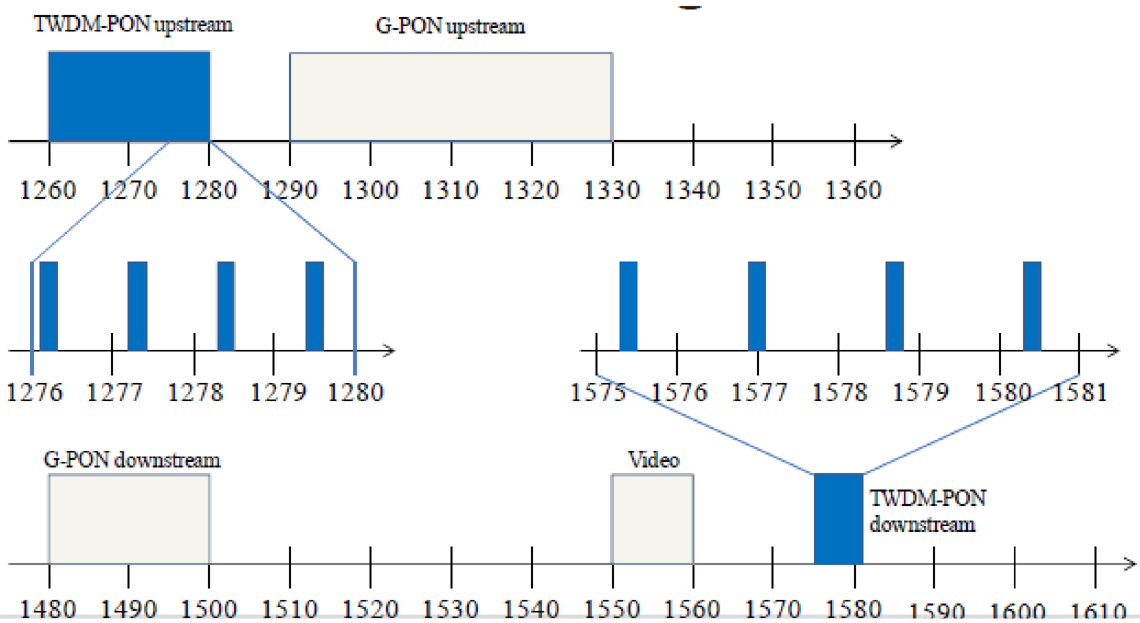


Figure 24: XG-PON Wavelength reuse [16]

In this option, the wavelength ranges proposed are in the wavelength ranges already defined for XG-PON.

The power budget of this type of network will depend on the above wavelength plans chosen. The main characteristics of both options are described on Table 6:

	C-band wavelength plan	XG-PON wavelength reuse
OLT launched power per channel	10.5 dBm	6 dBm
ONU receiver sensitivity	-28 dBm	-28 dBm
ONU launched power	2 dBm	2 dBm
OLT receiver sensitivity	-38 dBm	-31.5 dBm
Downstream OPP	1 dB	1 dB
Upstream OPP	0.5 dB	0.5 dB
Loss budget	37.5 dB	33 dB

Table 6: Power Budget [16]

As shown in the above table the C-band solution supports a higher loss budget while the XG-PON reuse has similar results to a XG-PON network.

The C-band wavelength plan however has the problem of using wavelengths defined for the G-PON guard band. For example, part of the band used for video transmission is being assigned for the downstream transmission in this type of network.

An example of this network solution is shown in Figure 25:

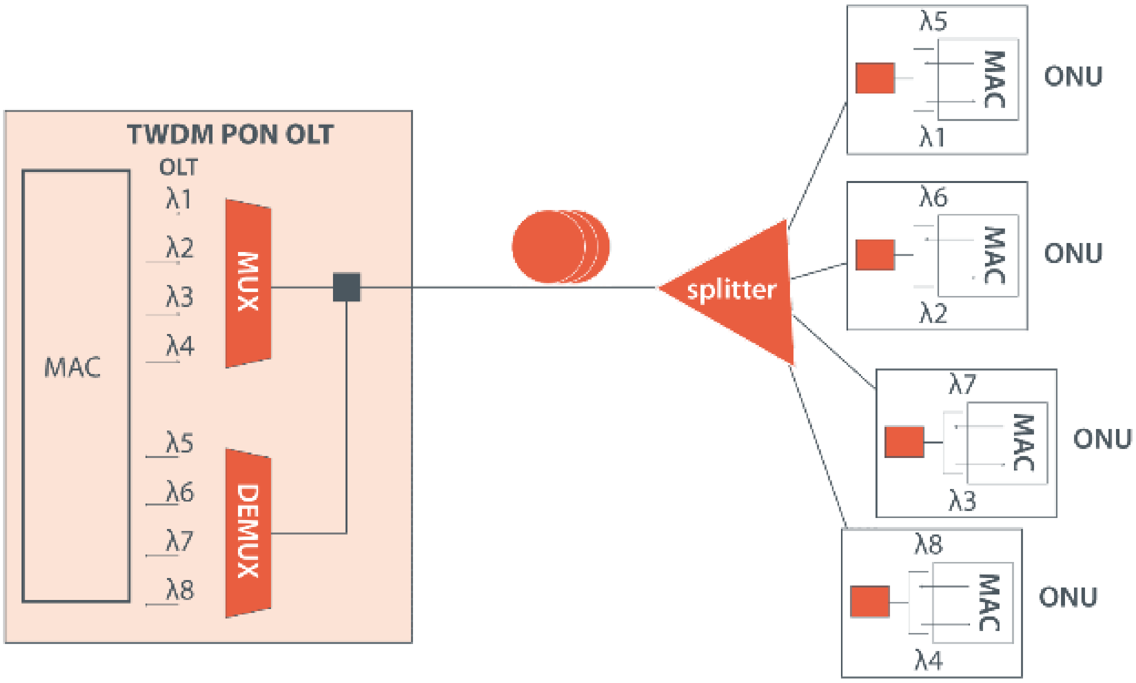


Figure 25: TWDM-PON [15]

As shown, it is possible for example to define a certain wavelength for each area, having a specific wavelength for downstream and one for upstream.

2.4.5 OFDM-PON

A study performed by Alcatel-Lucent [37] indicates another possible solution for a new PON network.

An example of how this solution works is presented on Figure 26.

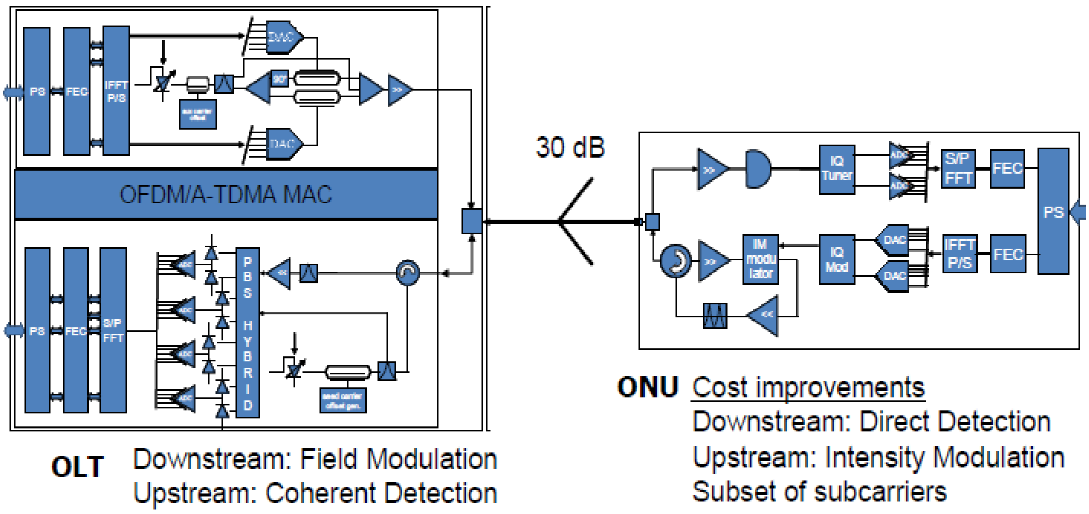


Figure 26: Asymmetrical Coherent OFDM-PON [37]

This solution has several noteworthy benefits such as: [37]

- High single carrier rate (High spectral density)
- 40-100 Gbit/s demonstrated
- Dispersion tolerance suited for long reach (100 km)
- Subcarrier frequency as multiple access dimension (can be further combined with time and wavelength)
- ONU needs to process only subset of spectrum and can operate at lower rates
- Ability to adjust link capacity power consumption to temporal traffic demands

Even though the benefits presented by this technology are appealing it has the severe disadvantage of being complex and having a high implementation and effective subscriber cost [37].

Due to the increased complexity and cost this solution is only used for testing as it would not be feasible to implement it in a large network.

3. WDM-PON Architecture

In this chapter the main components in a WDM-PON network with tunable components will be described in greater detail allowing a more in depth-study of its architecture.

The proposed solution is based on the equipment available at IT Aveiro for this purpose, and on the studies performed by colleagues in this institution, most notably Gonçalo Pereira [21].

Besides analyzing a network using tunable components, there is also a description of how SFPs work and their use in converting wavelengths in a network.

3.1 Tunable Lasers

As described above, the tunable lasers approach offers the best performance wise option in a WDM-PON network due to its high bit-rate and long transmission distance.

This solution consists of having a Tx/Rx (Transmit/Receive) pair for both the OLT and ONU with each wavelength. As the laser is tunable the Tx/Rx pair at the ONUs is tuned to their specific wavelength defined by the OLT.

There are several options available for a tunable laser, the more commonly used being DFB/DBR (Distributed feedback laser / Distributed Bragg Reflector) lasers, VCSELs (Vertical-Cavity Surface-Emitting Lasers) and ECLs (External Cavity Lasers) shown in Figure 27.

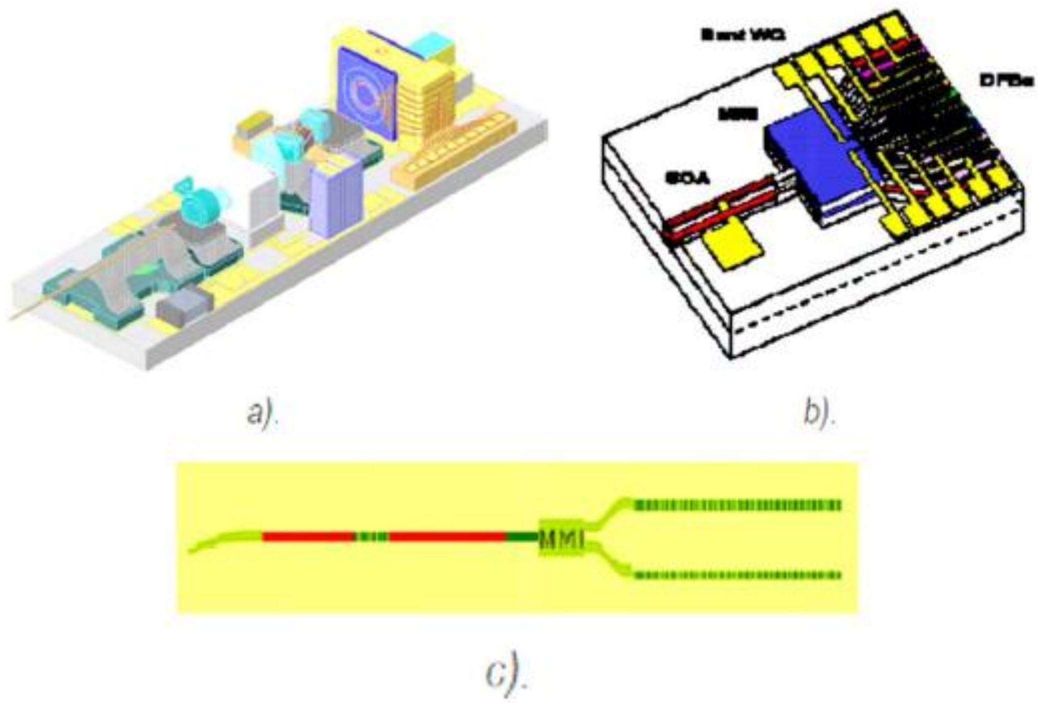


Figure 27: Typical TL (Tunable Laser) devices: (a) ECL, (b) DFB, and (c) DBR [19]

ECLs are tuned by changing the characteristics of their external cavity consisting of a grating or Fabry-Perot etalon. The main advantage of these lasers are the extremely wide tuning ranges but due to the long cavity length high-speed direct modulation is not possible which results in them not being an optimal solution for fiber communication as tuning speed and stability are other issues. [20]

DFB/DBR lasers are tuned by varying their temperature resulting in a possible wavelength range of little more than 3nm with temperature variances of more than 30ºC. An array consisting of 12 lasers is used so that it is possible to cover the required wavelength range of 30 to 35nm, however as the output from these lasers are required to be coupled into the same fiber a 12:1 combiner or a MEMS (Microelectromechanic System) mirror is required. Using a 12:1 combiner results in 11dB insertion loss that needs to be compensated to retain a reasonable power output, while by using a MEMS mirror the result is sensitive to vibrations and requires a high-voltage control. Using either option, there are still two major disadvantages inherent to DFB lasers. The power consumption is high and the tuning process is slow. [19]

VCELs consist of a gain medium between two oppositely doped distributed Bragg reflectors. These types of lasers are a potential source of low cost tunable lasers for access networks, however at the moment they are not a viable option due to unsatisfactory results. The tuning in VCELs uses a MEMS structure which changes the cavity length through electrostatic control. The tuning range can reach 10 to 20nm and its speed is a few microseconds. [20]

3.2 Tunable Receivers

A possible implementation for a tunable receiver consists of using a tunable optical filter and a broadband photodiode but even though the result is a simple solution, it is bulky and expensive [20]. As such, an alternative consisting of an MSM-based (Metal-Semiconductor-Metal) integrated CMOS (Complementary Metal-Oxide-Semiconductor) wavelength tunable optical receiver was proposed in [22].

There are several advantages in this solution most notably a low tuning speed as the wavelength is set electronically. Other noteworthy advantages are the channel spacing which by being limited by coherence length of the laser can be much less than the standard 50 GHz and the possibility of having spectral shaping to adapt to specific system applications. [20]

The main disadvantage of this implementation is the limited scalability of the integrated interferometer by becoming more complex as the number of wavelengths increases. This problem limits the use of a single device in a large network but can be softened by proper network design. [20]

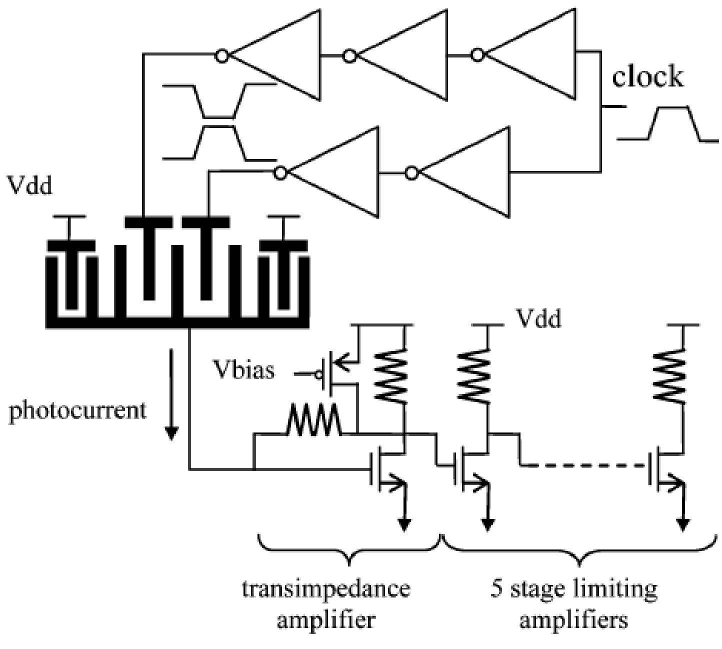


Figure 28: Schematic drawing of the CMOS tunable optical receiver and its detector driver [22]

As mentioned in the WDM-PON introduction a DWDM system has to be used as there is a need for a broad range of channels. These channels are spaced by 0.4 to 0.8 nm require an almost immunity to temperature variances. Due to these factors the implementation is costly derived from the need to have AWGs to cover a wide range of channels and lasers with precise temperature control. The option of using tunable lasers helps reduce the network cost compared to other options as every ONU uses the same type of components but the cost of each ONU is high.

Solutions based on low-cost tunable components are being developed to help alleviate the high cost inherent to its deployment.

In [23] one of these solutions is proposed with a 40 Gbit/s aggregate bandwidth ONU using low-cost tunable equipment with a 4-channel wavelength tunable receiver and emitter at 10Gbit/s.

On the OLT side the downstream transmission is achieved using a 10 Gbit/s CML transmitter comprised of a directly-modulated DFB laser chirp and an OSR (Optical Spectrum Reshaper) passive optical element managing the laser chirp. The CML (Chirp Managed Laser) is driven directly by a PPG (Pulse Pattern Generator), and performance is measured using a BERT (Bit Error Ratio Tester). The VOA (Variable Optical Attenuator) is employed to simulate link loss and CDR is a clock/data recovery circuit.

On the ONU a low cost tunable receiver manufactured by Aegis Lightwave is used. This tunable receiver is comprised of a tunable semiconductor thin film Fabry-Perot filter, an APD (Avalanche Photodiode) and a TIA (Trans-Impedance Amplifier). For bandwidth compensation an EDC (Electronic Dispersion Compensation) was used as the receiver is designed only for 2.5 Gbit/s.

The following figure shows the experimental setup used to test the downstream transmission:

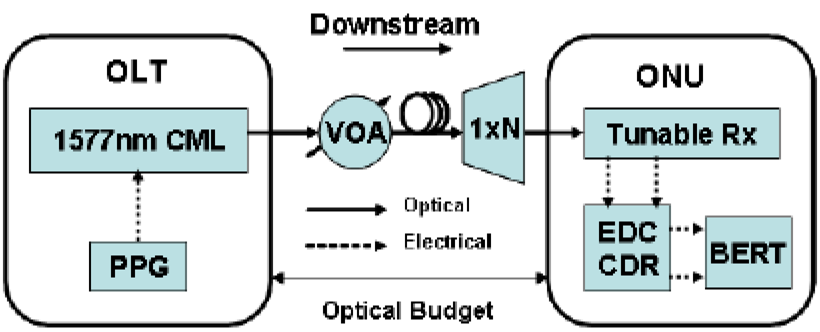


Figure 29: Experimental set-up of an NG-PON solution with a colorless ONU and EDC [23]

As for the upstream signal at the ONU a T-ECL (Tunable External Cavity Laser) comprised of a SLD (Super-Luminescent Laser Diode) and a polymeric tunable Bragg reflector was designed for 2.5 Gbit/s but driven to 10 Gbit/s by the PPG with PRBS (Pseudo-Random Bit Sequence) of length 27-1 coded in a NRZ modulation format with 2Vpp amplitude. A VOA is again used to simulate link loss.

On the OLT receiving side an APD is used at 10 GHz assisted by an EDC. The other OLT components are used in the same manner as for the ONU on the downstream transmission.

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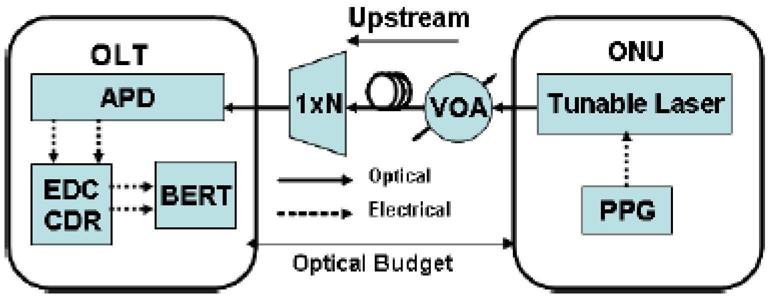

Figure 30: Experimental setup of NG-PON solution with colorless ONU and EDC using NRZ signal [23]

Even though this solution presents the possibility of having a lower cost solution using tunable components the example shown only uses 4 channels, by increasing the number of channels the costs will increase and as such while being an important step in finding a feasible low cost solution more research needs to be done in this area before a network implementation is possible. Another problem with this solution is in the transmission distance. With the setups shown above it was only possible to have an acceptable BER (Bit Error Rate) with downstream distances up to 40km and upstream up to 20 km.

3.3 SFPs

A SFP (small form-factor pluggable) transceiver is a compact, hot-swappable, input/output transceiver used in data communication and telecommunications networks. SFP interfaces between communication devices like switches, routers and fiber optic cables, and performs conversions between optical and electrical signals. [24]

Paper [25] proposes a wavelength-tunable and large power budget DWDM-SFP transceiver for the L-band that has a signal monitoring. This solution enables the construction of a coexistence-type colorless WDM-PON employing the following technologies:

- Remote initial wavelength setting procedure
- Centralized wavelength monitor/stabilization technique

Using this DWDM-SFP transceiver a tunable ONU and a WDM-OSU (optical subscriber unit) with a wavelength monitor (A-monitor) for the upstream signal is demonstrated and the feasibility of the coexistence-type WDM-PON is verified.

Figure 31 shows an example of the coexistence of an existing PON and the colorless WDM-PON, while Figure 32 demonstrates the proposed DWDM-SFP transceiver configuration.

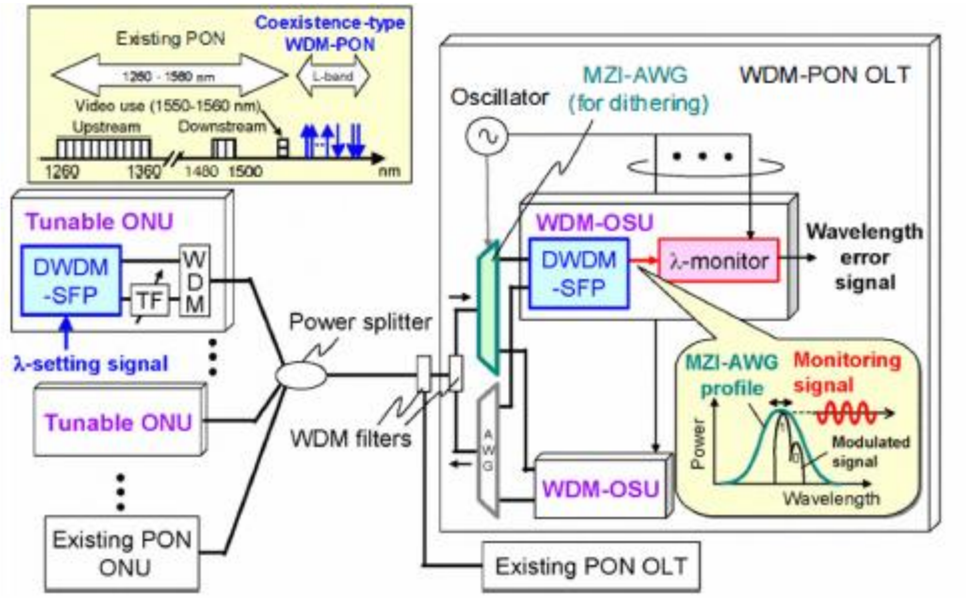

Figure 31: Coexistence-type colorless WDM-PON using proposed DWDM-SFP transceivers [25]

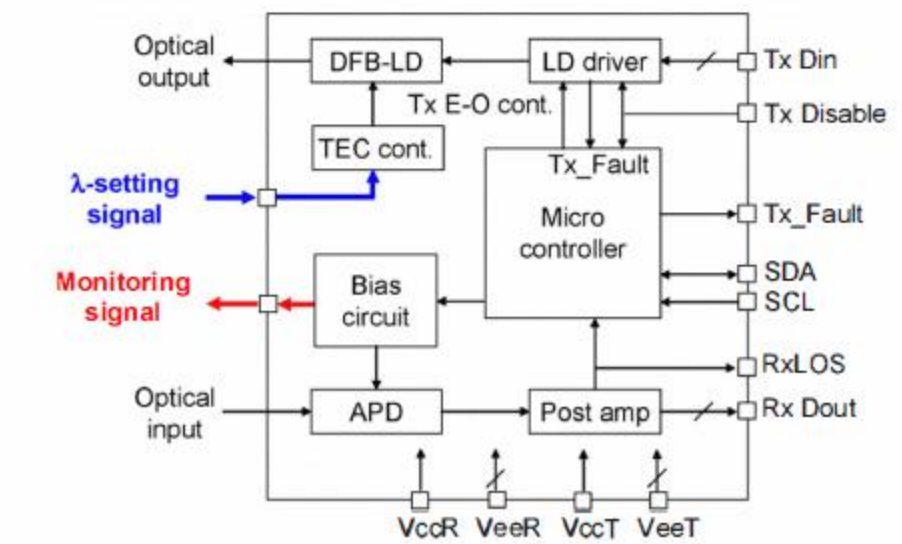

Figure 32: Proposed DWDM-SFP transceiver configuration [25]

The above paper demonstrates the importance and relevance of using SFPs in a WDM-PON network as the solution presented demonstrated its possible coexistence with existing PON networks.

3.4 WDM-based GPON hybrid

An example of this type of network can be found on the MEL telecom solutions called WTG32 [33]. This example is shown on Figure 33.

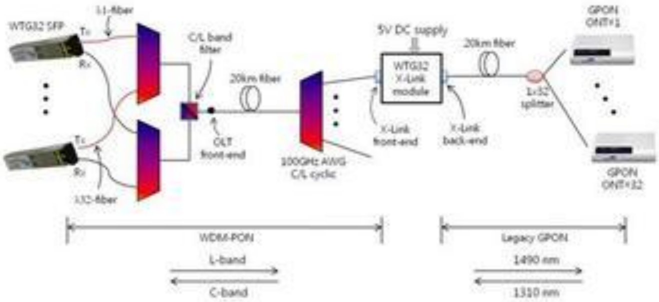

Figure 33: WTG32 optical link [33]

This network shows a solution to combine the available GPON networks with a WDM-PON link by using an X-Link module between them for wavelength conversion as demonstrated on Figure 34.

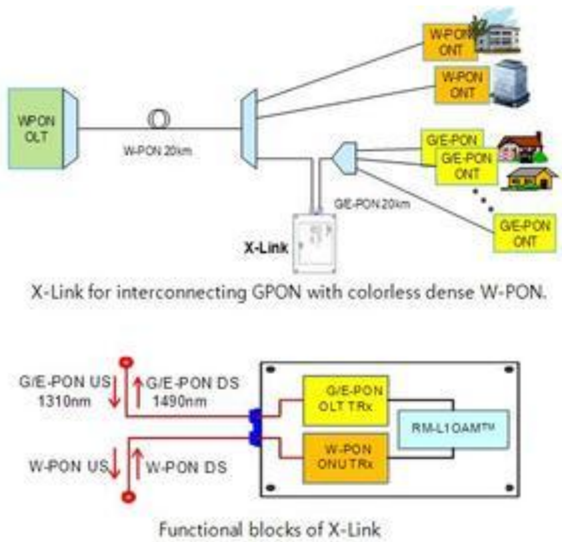

Figure 34: WTG32 X-Link [33]

The X-Link module comprises of a WDM-PON OTRx for interfacing the WDM-PON link, and a GPON SFP OTRx for interfacing legacy GPON link. In a WDM-PON OTRx, its transmitter is a wavelength-pluggable transmitter of which the output wavelength can be switched from one to another within C-band or within L-band by simply plugging into the receptacle the wavelength-assigned fiber connector (lambda-connector), which is offered along with the X-Link module. The lambda-connector has a special part inside the connector for wavelength selection while its mechanical appearance is the same as the LC/APC commercial patch cord. The wavelength selection range covers 32 wavelengths with 100 GHz spacing in C-band or in L-band. [33]

For remotely gathering the OAM information on the status of the X-Link module, the X-Link module has a special function of delivering the information on its internal status in the physical layer (Layer 1) to the remotely-located WTG32 SFP Rx. The WTG32 SFP receiver is designed to receive the OAM information and the GPON OLT system can access it via I2C interface. [33]

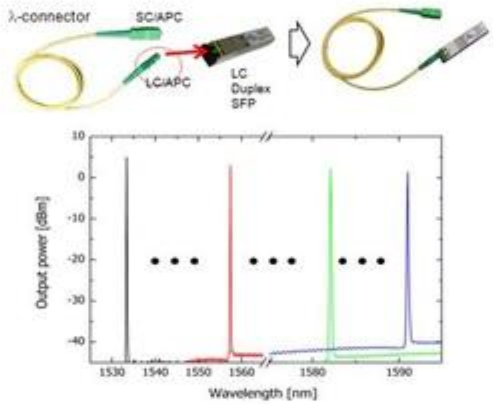

Figure 35: WTG32 OLT SFP [33]

Using this equipment it is possible to evolve the current networks to a WDM-PON solution while still maintaining part of the network, as such the conversion is not as expensive as other options and the reach can be extended.

4. Laboratory Equipment

In order to perform the laboratory tests relevant to this dissertation, a wide array of equipment is needed and as such this chapter will describe the main parameters relevant to this work.

4.1 SFPs

For this dissertation the following SFPs will be used:

FTLF1621P2BCL [26]

SFP made by Finisar with its main characteristics being the 1550 nm DFB laser transmitter and the possibility of having up to 2.67 Gbit/s bi-directional data links.

In terms of optical characteristics relevant for the purpose of this dissertation we have the following parameters:

Receiver wavelength: 1270 to 1600 nm
Receiver sensitivity: -9 to -28 dBm
Transmitter output power: -2 to +3 dBm

FTLF1319P1BTL [27]

SFP made by Finisar with its main characteristics being the 1310 nm Fabry-Perot laser transmitter and the possibility of having up to 2.125 Gbit/s bi-directional data links.

Optical characteristics;

Receiver wavelength: 1265 to 1600 nm
Receiver sensitivity: max -21 dBm
Transmitter output power: -9.5 to -3 dBm

SPL-94B73B-WG [29]

SFP made by Optoway with a 2.488 Gbit/s 1490 nm Continuous-Mode Transmitter and a 1.244 Gbit/s / 1310 nm Burst-Mode Receiver with 2R Output.

Optical characteristics;

Receiver wavelength: 1260 to 1360 nm
Receiver sensitivity: -8 to -28 dBm
Transmitter output power: +1.5 to +5 dBm

4.2 GPON

4.2.1 OLT

The OLT used for the GPON network is shown on Figure 36:

Figure 36: GPON OLT

This OLT has 8 PON slots supporting 64 clients each and 8 Ethernet interfaces. The first is used to connect the OLT to the traffic generator IXIA. The OLT also has 2 additional Ethernet interfaces and a RS232 port for equipment configuration.

Table 7 shows this OLT's main characteristics:

Manufacturer	PT Inovação
Model	OLT7-8CH
Transmitter wavelenght	1490 nm
Receiver wavelength	1310 nm
Trasmit power (MGPON datasheet)	+5<Pout<+6 dBm
Trasmit power (measured)	3.6 dBm
Maximum receive power (MGPON datasheet)	-10 dBm
Receive sensitivity (MGPON datasheet)	-31 dBm
Transmit rate	2.5 Gbps
Receive rate	1.25Gbps
Connector type	SC-PC
Power supply	DC -48V
Working temperature	-5ºC to 50º C

Table 7: GPON OLT characteristics

Important parameters to note in this OLT's characteristics are the wavelengths being used, the commonly used values in a GPON transmission, the transmit power of the OLT which is important to confirm in order to design the network based on it and the receive sensitivity for the same reason as the transmitted power. The transmit rate is also an important parameter however as will be explained further on, due to the IXIA equipment limitations if the rate is above 1Gbit/s it will not make a difference.

4.2.2 ONU

Figure 37 shows the ONU used in the GPON laboratory tests:

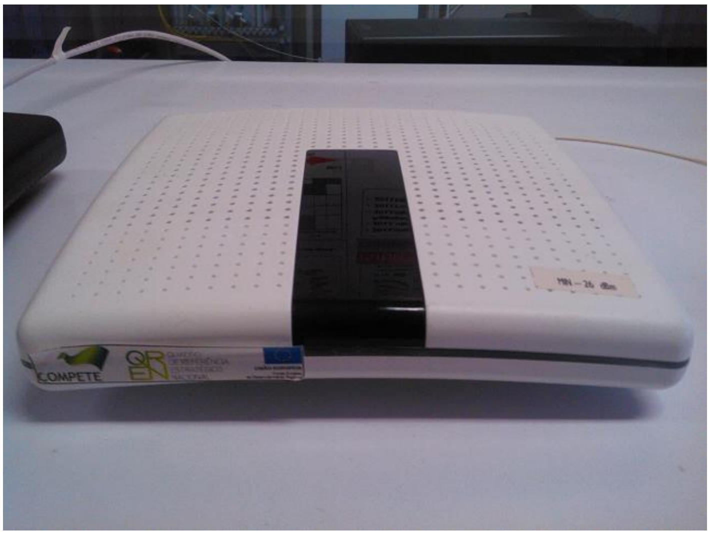

Figure 37: GPON White ONU

Looking at the image of the ONU the only distinctive feature is the front panel, where the light turns on if the ONU is not receiving.

In the rear panel there is a power supply connector and the optical line connection.

The main characteristics of this ONU are represented in Table 8:

Manufacturer	PT Inovação
Model	PTINONT7RF1GE
Transmitter wavelenght	1310 nm
Receiver wavelength	1490 nm
Trasmit power (MGPON datasheet)	+1 to +6 dBm
Maximum receive power (MGPON datasheet)	-8 dBm
Receive sensitivity(MGPON datasheet)	-27 dBm
Transmit rate	1.25 Gbps
Receive rate	2.5 Gbps
Connector type	SC-APC
Power supply	DC +12V
Working temperature	

Table 8: GPON ONU characteristics

As for the OLT, the main parameters to take note for the ONU are: transmitter and receiver wavelength, transmitted power and receive sensitivity. The reasons are the same as before.

There is another ONU available at the laboratory which will also be used to test the GPON network. This 2nd ONU is shown on Figure 38:

Figure 38: GPON Black ONU

This ONU has similar characteristics to the white ONU but has a lower sensitivity (-25 dBm) which will be useful for the tests performed in the network.

4.2.3 Web Interface

To configure and access the OLT a web interface can be accessed through Ethernet in the Ethernet port 1.

Using this interface several parameters can be defined, for example the logical distance.

Even though it is possible to change some parameters on this interface, for the tests being performed in this dissertation this option is mostly irrelevant as the parameters being changed are due to the IXIA performance tester described in the next sub chapter and in the network equipment.

4.2.4 IXIA packet generation

To simulate network traffic the IXIA IP Performance Tester will be used.

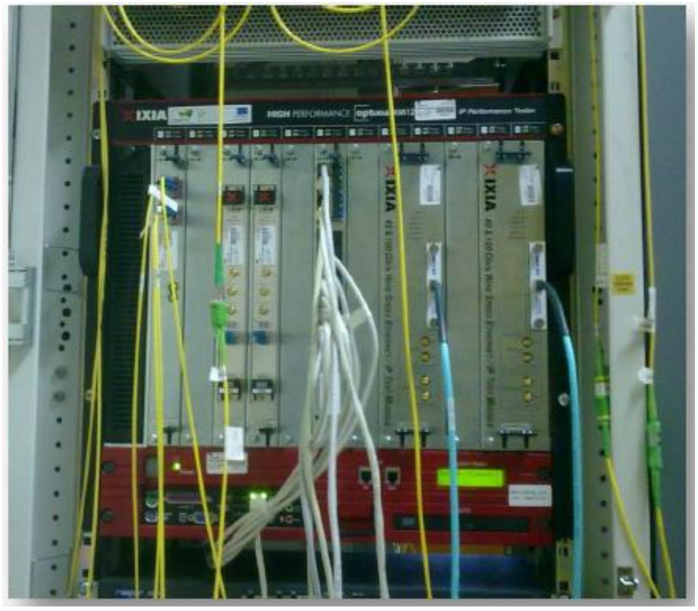

Figure 39: IXIA Optixia XM12 equipment

Using this equipment it is possible to define the transmission rate of the network up to 1 Gbit/s and analyze the results achieved on the network. The main parameter for these simulations is the percentage of packet loss as it defines the quality of the signal received by the OLT or ONU.

An important point to note with using the IXIA to test the network is that as mentioned, the transmission rate can only be set up to 1 Gbit/s. By having this limitation the results obtained cannot be compared in detail with a field implementation of a GPON network.

4.3 EPON

4.3.1 OLT

The OLT used for the EPON tests is shown in Figure 40:

Figure 40: EPON OLT

This OLT has 2 cards. Each of these 2 cards has 2 ports each one supporting a PON network resulting in a possible 4 PON connections.

For the tests performed in the laboratory only 2 of the available PON connections are used, the first one in each card.

The main characteristics of this OLT are displayed in Table 9:

Manufacturer	FiberHome
Model	AN5116-02
Transmitter wavelenght	1490 nm
Receiver wavelength	1310 nm
Trasmit power (standard)	+2 to +7 dBm
Trasmit power (measured)	+3 to +5 dBm
Maximum receive power	-6 dBm
Receive sensitivity (standard)	-27 dBm
Receive sensitivity (measured)	-27 dBm
Transmit rate	1.25 Gbps
Receive rate	1.25 Gbps
Connector type	SC-PC
Power supply	DC -48V
Working temperature	0ºC to 45ºC

Table 9: EPON OLT Characteristics

Observing the OLT characteristics present, the most noteworthy parameters are mostly the same as mentioned in the case of the GPON. There is however an important difference to note, the transmit rate. In this case the transmit rate is half the one obtained with the GPON OLT which even though it will not affect the tests due to the specified IXIA limitations it is still an important disadvantage in relation to the available GPON equipment.

4.3.2 ONU

The ONU used is the following:

Figure 41: EPON ONU

Observing the image of the ONU in Figure 41, it is obvious the amount of indicators when compared with the GPON ONU shown in Figure 37. There are 6 ONUs available at the laboratory, 3 of them having a triplexer inside with an RF output while the others have not. Besides the mentioned difference in indicators related to such things as loss of signal, power status, registry on the EPON system there are also several more connections in the rear panel. Apart from the power supply connector there is a console port, 2 fixed FXS ports for general phone line, 1 EPON port(SC-APC for ONUs with RF output and SC-PC for ONUs without RF output) and 1 CATV RF connector.

The main characteristics of the ONUs available are described in Table 10:

Manufacturer	FiberHome
Model	AN5006-05
Transmitter wavelenght	1310 nm
Receiver wavelength	1490±10 nm
Trasmit power (standard)	-1 to +4 dBm
Trasmit power (measured)	+4 dBm
Maximum receive power	-3 dBm
Receive sensitivity (measured)	-24 dBm
Receive sensitivity (measured)	-28 dBm
Transmit rate	1.25 Gbps
Receive rate	1.25 Gbps
Connector type	SC-PC/SC-APC
Power supply	DC +12V
Working temperature	-10ºC to 45ºC

Table 10: EPON ONU Characteristics

As before, the main parameters to take note from this table are the wavelengths being used, the transmitted power and receive sensitivity.

4.3.3 IXIA Packet Generation

As with the GPON experiments to generate traffic in the network in a laboratorial environment the IXIA IP performance tester will be used to test the networks main characteristics in terms of transmission rate and power budget.

4.4 Triplexer WDM coupler

The triplexer available at the laboratory is a 1x3 triplexer WDM coupler by oeMarket. It can be used to either multiplex or demultiplex three channels at specific wavelengths of 1310 nm, 1490 nm and 1550 nm. All three wavelengths can be introduced at the common port and filtered into separate output ports. [34]

The wavelengths filtered by this triplexer are the specific ones used by a common GPON network and as such are used in several tests in this dissertation in order to better characterize each transmission separately. Its main characteristics are described in Table 11:

Parameter	Unit	Values
Central wavelength	nm	1310, 1490, 1550
Passing band	nm	1490±10
Reflection bands	nm	1310±50 & 1550±10
Insertion loss @ 1490nm	dB	⩽0.8 (0.6 typical)
Insertion loss @ 1310nm	dB	⩽0.6 (0.4 typical)
Insertion loss @ 1550nm	dB	⩽1.0 (0.8 typical)
Isolation @ 1490nm	dB	⩾35
Isolation @ 1310nm	dB	⩾25
Isolation @ 1550nm	dB	⩾20
Directivity	dB	⩾55
Return loss	dB	⩾50
PDL	dB	⩽0.1
Wavelength thermal stability	nm/ºC	⩽0.003
Insertion loss thermal stability	dB/ºC	⩽0.005
Power handling	mW	⩽500
Operating temperature	ºC	−40 ~ +85
Storage temperature	ºC	−40 ~ +85
Dimensions	mm	Φ5.5×L50

Table 11: Triplexer Specifications [34]

As already mentioned the wavelengths being filtered are the ones used in a GPON network, however another important parameter described in its characteristics are the insertion loss for each wavelength. It is paramount to note this loss in power to better adapt the network if needed.

5. Experimental Results

5.1 GPON with one ONU

For the purpose of characterizing the GPON network present at the laboratory the following architecture was put in place:

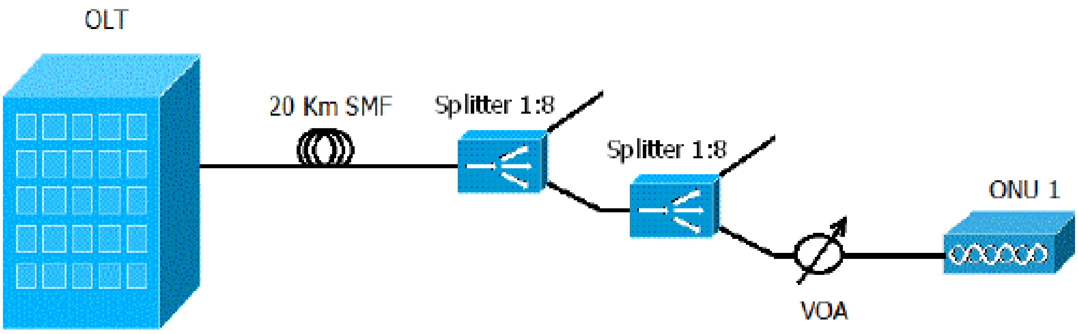

Figure 42: GPON network with one ONU

Usually GPON networks deployed in the field use a 1:64 splitter to support a maximum of 64 clients however as that equipment is expensive and not available at the laboratory similar results are obtained by using two 1:8 splitters in cascade mode. To better characterize this network and study the power budget available, a VOA (Variable Optical Attenuator) is also used to verify the minimum possible power with which the ONU still receives the information transmitted by the OLT.

The two main characteristics of the available equipment that will be analyzed in the following subchapters are the maximum transmission rate with which there are no frame loss and the maximum power budget supported by the network. Both of these tests will be performed separately for each available ONU.

5.1.1 Maximum Transmission Rate with white ONU

As described in the laboratory equipment chapter by using an IXIA IP performance tester it is possible to transmit data in this network to test several of its characteristics. In this case by varying the line rate of the information being transmitted both upstream and downstream, it is also possible to verify the percentage of packet loss due to increasing the line rate up to the maximum possible value permitted by this equipment.

Table 12 and Figure 43 show the results obtained by varying the line rate simultaneously for both upstream and downstream. The results shown were obtained by transmitting 1 million frames.

Line Rate (Mbit/s)	Downstream Frame Loss (%)	Upstream Frame Loss (%)
600	0	0
650	14.12	0
700	24.4	5.2
750	30.4	12.6
800	35.5	19.8
850	39.96	26.1
900	44	31.8
950	47.6	36.7
976	49.35	39

Table 12: GPON downstream and upstream frame loss for various line rates with white ONU

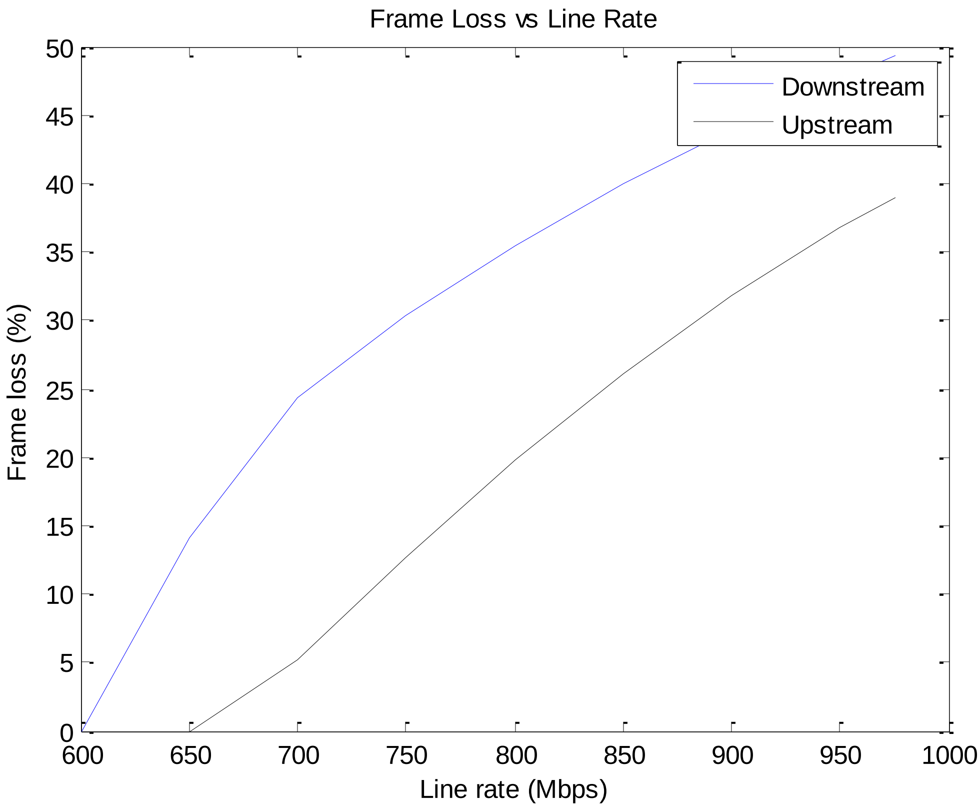

Figure 43: GPON downstream and upstream frame loss for various line rates with white ONU

The results shown above are only for line rates between 600 Mbit/s and 976 Mbit/s as values below this interval have a 0% frame loss and as the IXIA has a 1 Gb card, the maximum possible line rate is only approximately 1Gbit/s (in this case 976 Mbit/s). Figure 43 shows that after 600 Mbit/s there is frame loss for the downstream transmission, while for the upstream transmission the frame loss occurs after 650 Mbit/s. The frame loss increases up to almost 50% at maximum downstream transmission rate and ~40% in upstream, as shown on Table 12.

With these results it was possible to conclude that for further testing a line rate below 600 Mbit/s is preferable to minimize frame loss.

5.1.2 Maximum Power Budget with white ONU

As explained above, the architecture being used for this network tries to simulate as faithfully as possible the conditions present at a field deployed network. As such, one of the most important parameters to define is the maximum power budget to find out how much splitters can be used and the length of fiber possible to implement without frame loss. Knowing from the above test that there is no frame loss below a line rate of 600 Mbit/s, in this example the transmission will be done at 400 Mbit/s and once again a million frames are transmitted in each test.

Figure 44 displays the architecture being used while also indicating the power being transmitted and the relevant power losses in each piece of equipment.

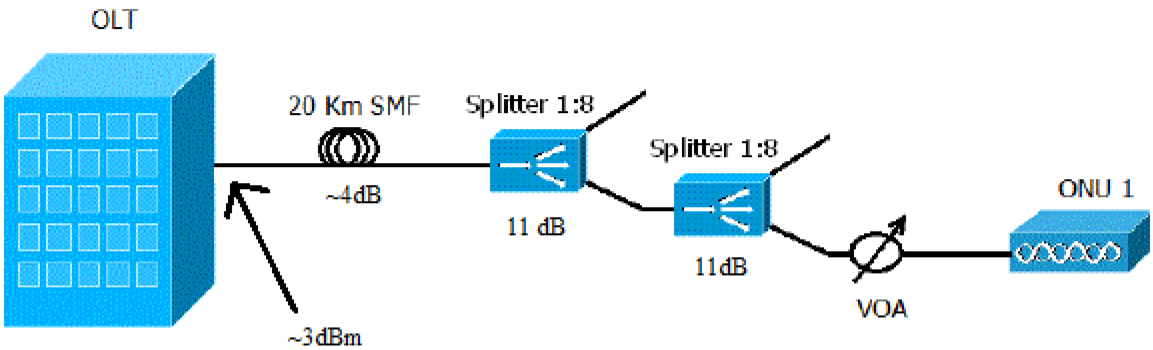

Figure 44: GPON network power budget

The ~4 dB loss in the 20 km fiber is the approximate value for 1550 nm. If considering for example 1310 nm, the wavelength used for the upstream signal this value will be significantly higher (around 7 dB) but since it is not possible to measure the power of the upstream signal being transmitted the power budget of the network is being considered in a downstream perspective and as such the 4 dB loss on the 20 km fiber is a reasonable approximation.

As shown in Figure 44 the signal transmitted by the GPON OLT had a power value of 3 dBm. Using the values presented for attenuation on the network it is possible to calculate the power at the ONU using the following formula:

$$P_{onu} = 3\text{ dBm} - 4\text{ dB} - 11\text{ dB} - 11\text{ dB} - VOA$$
$$P_{onu} = -23\text{ dBm} - VOA$$

Knowing the power available at the ONU it is possible to calculate the power budget of the network:

$$PB = P_{olt} - P_{onu}$$
$$PB = 26\text{ dB} + VOA$$

As the ONU has a labeled sensitivity of -27 dBm by using the VOA it is possible to reduce the power even further to define the maximum power budget available. Using this method the following results were obtained:

VOA attenuation (dB)	Downstream Frame Loss (%)	Upstream Frame Loss (%)
5.1	0	0.013
5.2	0	0.035
5.3	0	0.56
5.4	0	1.7
5.5	0	4.7
5.6	100	100

Table 13: VOA attenuation and frame loss with white ONU

Adding the above attenuation in the VOA as explained in the formula, it is possible to create a graph showing the frame loss percentage in comparison to the supported power budget in the network.

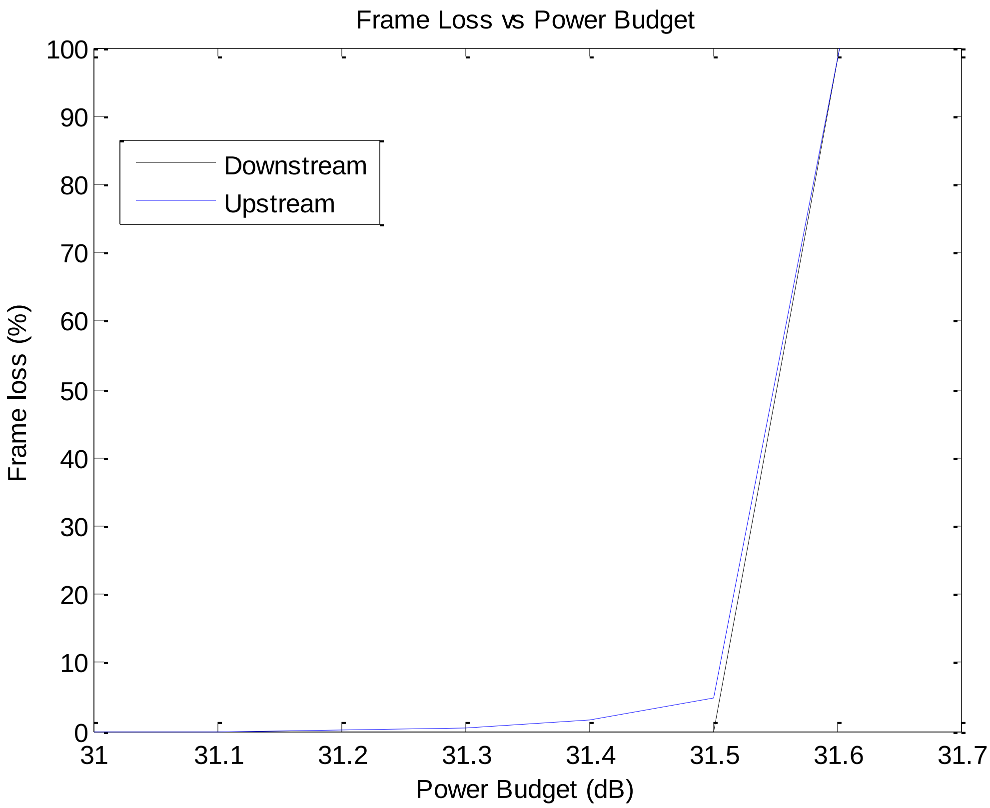

Figure 45: GPON frame loss vs. power budget with white ONU

The results presented are only for values below -28 dBm at the ONU as with more power the frame loss was still 0%. From the available results, it is possible to conclude that the maximum power budget without any frame loss on the network is approximately 31 dB while by increasing this value the upstream signal start losing frames up to the 31.6 dB which results in both transmissions not reaching its destination.

5.1.3 Maximum Transmission Rate with black ONU

Using the same procedure described for this test using the white ONU the following results were obtained using the black ONU:

Line Rate (Mbit/s)	Downstream Frame Loss (%)	Upstream Frame Loss (%)
600	0	0
650	1.84	14.37
700	16.36	25.19
750	25.9	33.06
800	31.47	37.15
850	36.49	40.12
900	40.86	42.93
950	44.87	45.42
976	46.77	46.72

Table 14: GPON downstream and upstream frame loss for various line rates with black ONU

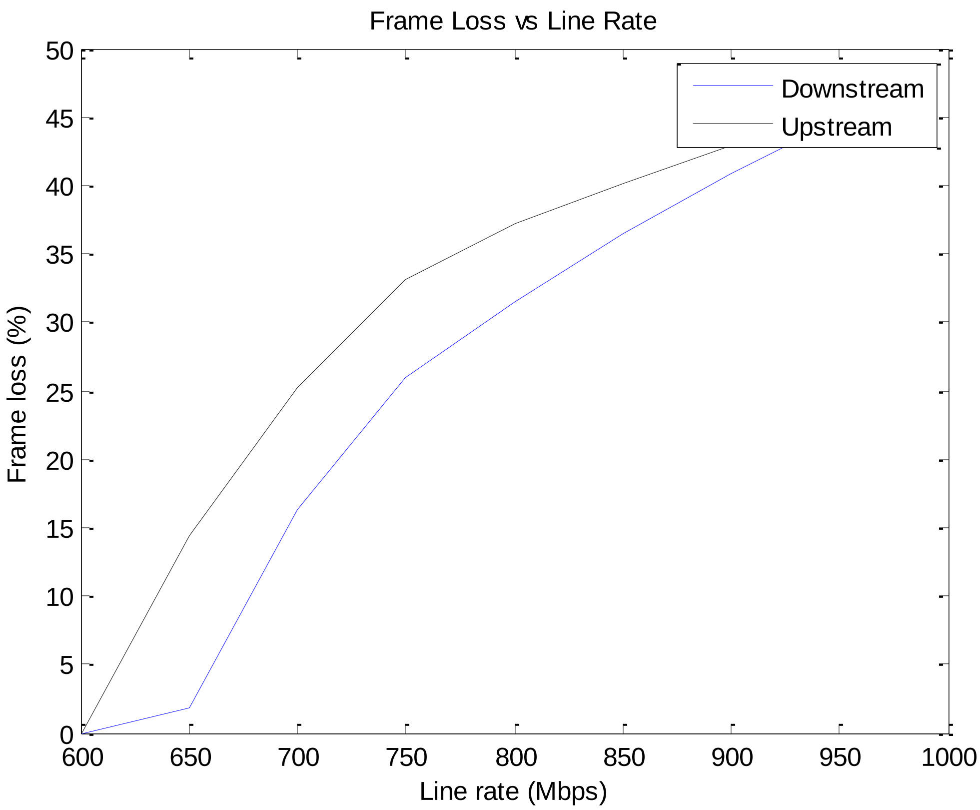

Figure 46: GPON downstream and upstream frame loss for various line rates with black ONU

The results obtained with this ONU are similar than those with the white ONU. For line rates below 600 Mbit/s there are no frame loss but by increasing the rate above that value the loss percentage increases up to almost 50% with maximum possible line rate using the IXIA 1 Gb card.

5.1.4 Maximum Power Budget with black ONU

As the network architecture being used with this ONU is the same as with the white ONU, the procedure will be the same to deduce the maximum power budget. This ONU has a labeled sensitivity lower than the white ONU and as such the attenuation used in the VOA will be lower as shown below:

VOA attenuation (dB)	Downstream Frame Loss (%)	Upstream Frame Loss (%)
3	0	0.01
3.2	0	0.02
3.4	0	0.033
3.6	0	1.62
3.7	0	3.97
3.8	0	23.83
3.9	0	29.54
4	100	100

Table 15: VOA attenuation and frame loss with black ONU

As with the previous case by adding the VOA attenuation displayed in the table it is possible to compare the power budget in the network with its frame loss:

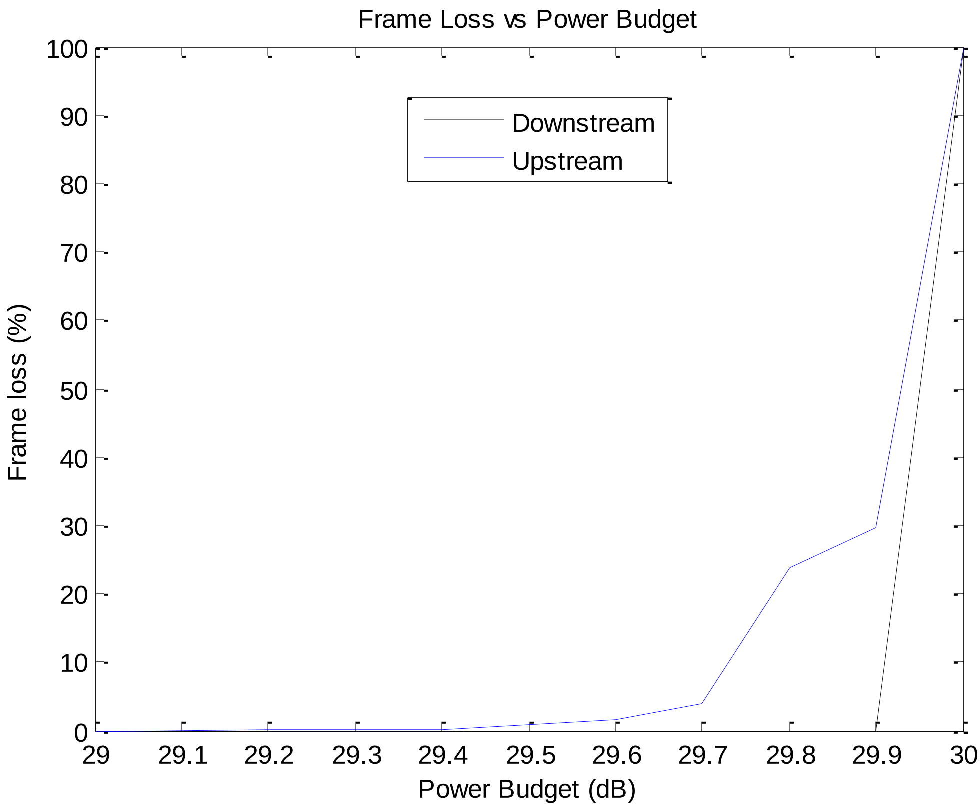

Figure 47: GPON frame loss vs. power budget with black ONU

As expected this ONU has a lower sensitivity and as such with a power budget of around 29.5 dB there are already some losses on the network. By increasing the power budget to 30 dB resulting in -26 dBm on the ONU the light turns on indicating that the ONU is not receiving as shown by the 100% frame loss.

5.2 GPON with two ONUs

To test the GPON network using two ONUs some changes were necessary in the network architecture as shown in Figure 48:

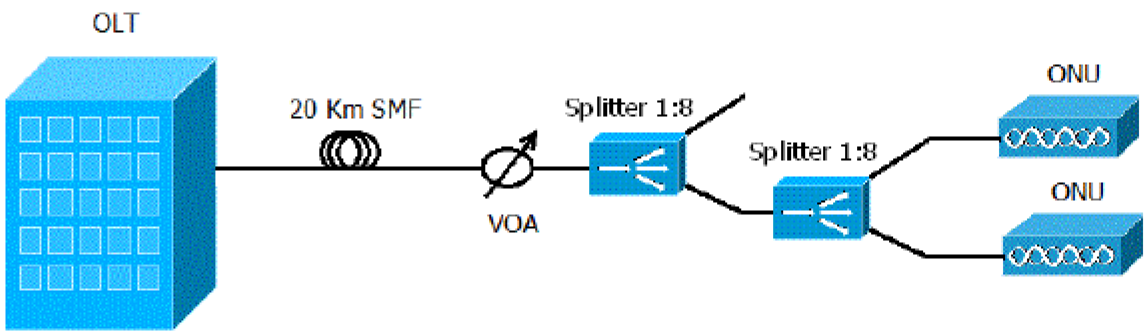

Figure 48: GPON network with two ONUs

With the intent of performing the same tests shown above for one ONU in this case it was necessary to change the VOA position to before the splitter so that both ONUs are affected by its attenuation.

This setup is also shown in this photo taken in the laboratory when performing the following tests:

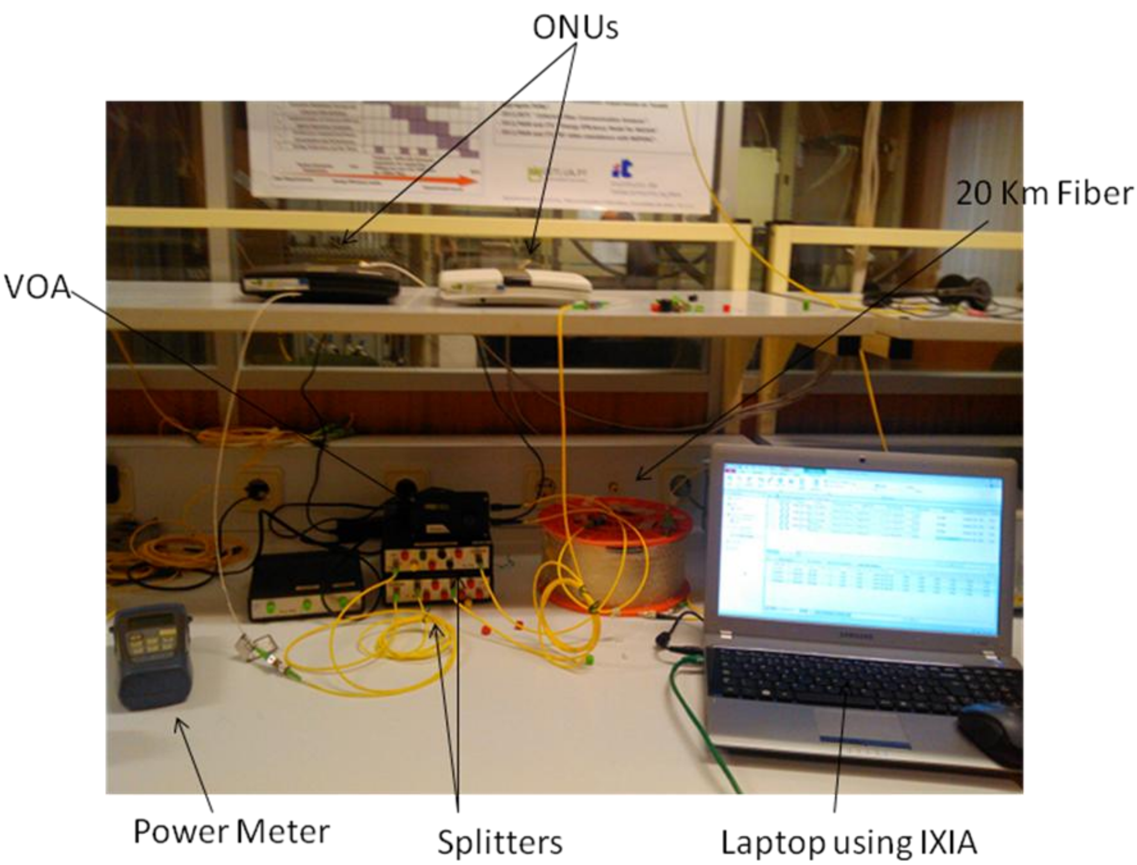

Figure 49: Photo of the equipment used in GPON tests

5.2.1 Maximum Transmission Rate with two ONUs

As above, by using the IXIA IP Performance Tester it is possible to simulate traffic in the network and study the effect of increasing the line rate in terms of frame loss. In this case as there are two simultaneous ONUs transmitting using the same IXIA card of 1Gbit/s the maximum possible line rate permitted is half of the previous value (976/2 = 488 Mbit/s).

The results obtained are shown on Table 16 and Figure 50:

Line Rate (Mbit/s)	Downstream Frame Loss Black ONU (%)	Upstream Frame Loss Black ONU (%)	Downstream Frame Loss White ONU (%)	Upstream Frame Loss White ONU (%)
450	0	0	0	0
460	0	0.085	0	0
465	0	1.11	0	0
470	0	3.84	0	0
475	0	8.02	0	0
480	0	11.86	0	0
485	0	15.68	0	0
488	0	17.75	0	0

Table 16: GPON downstream and upstream frame loss for various line rates with both ONUs

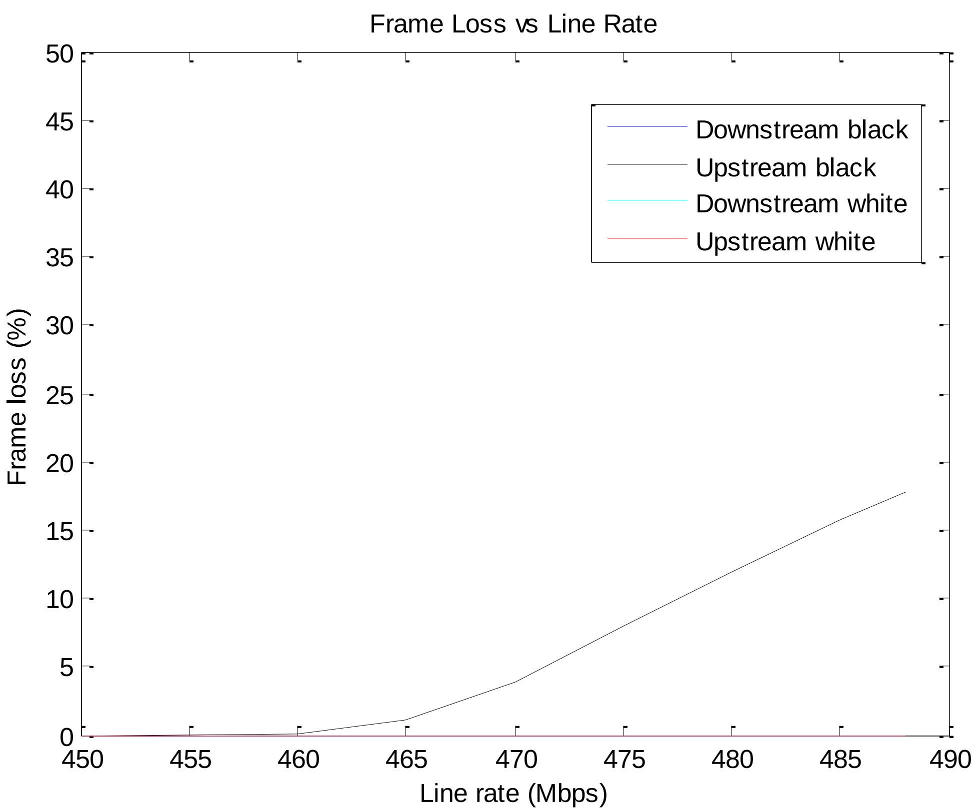

Figure 50: GPON downstream and upstream frame loss for various line rates with both ONUs

The results obtained show that by increasing the line rate of all transmissions in the same manner only the upstream signal from the black ONU has frame loss when reaching values close to the maximum permitted line rate of 488 Mbit/s.

5.2.2 Maximum Power Budget with two ONUs

To perform this test, the procedure is the same as with just one ONU as even though the VOA is in a different position on the network the attenuation between the OLT and each ONU is still the sum of the 20 km fiber, both splitters and the VOA. As such to define the maximum power budget of the network once again the VOA will be used to define the sensitivity of both ONUs when being used simultaneously.

VOA attenuation (dB)	Downstream Frame Loss Black ONU (%)	Upstream Frame Loss Black ONU (%)	Downstream Frame Loss White ONU (%)	Upstream Frame Loss White ONU (%)
3	0	0.01	0	1.33
3.1	0	0.013	0	2.97
3.2	0	0.03	0	15.06
3.3	0	0.04	0	29.57
3.4	0	0.13	100	100
3.5	0	0.15	100	100
3.6	0	0.18	100	100
3.7	0	0.25	100	100
3.8	0	0.5	100	100
3.9	0	1.57	100	100
4	0	5.56	100	100
4.1	11	22	100	100
4.2	100	100	100	100

Table 17: VOA attenuation and frame loss with both ONUs

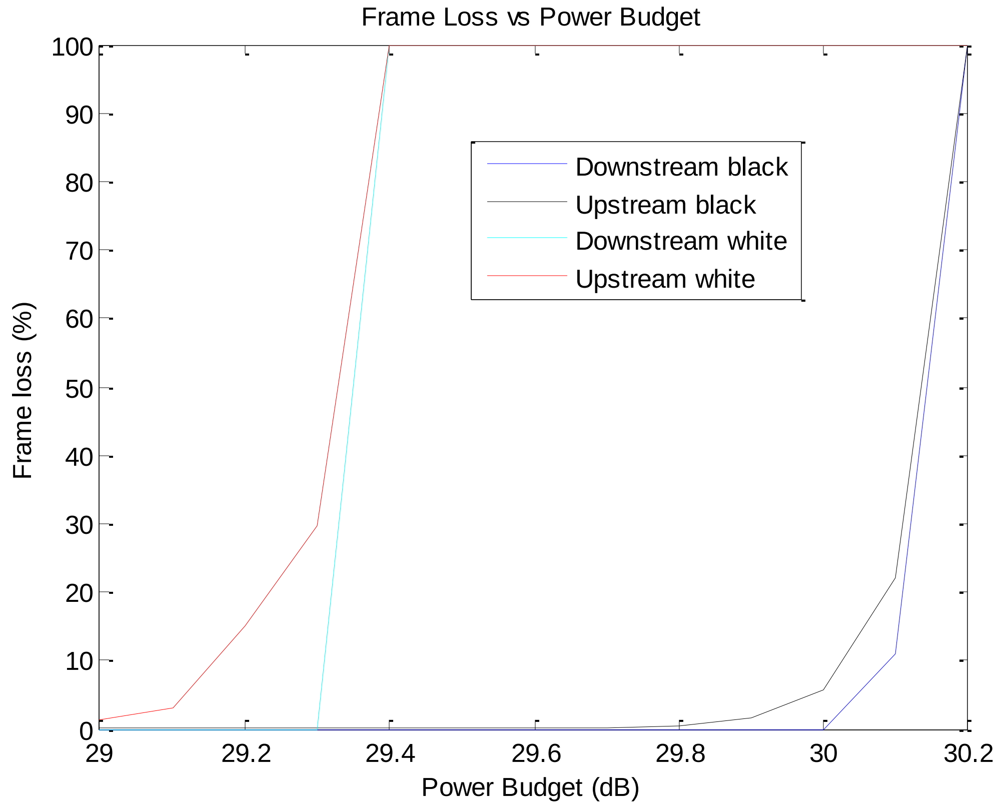

Figure 51: GPON frame loss vs. power budget with both ONUs

By observing the above graphic it is possible to conclude that when both ONUs are connected the white ONU stops transmitting with approximately -26.3 dBm and the black ONU at around -27.2 dBm.

These results were confirmed by the ONUs lights turning on at those values indicating that the ONU is no longer transmitting.

5.3 Wavelength converter

5.3.1 GPON OLT and ONU

In order to test the wavelength converting equipment the first test will be to introduce this conversion in a GPON network as shown on Figure 52:

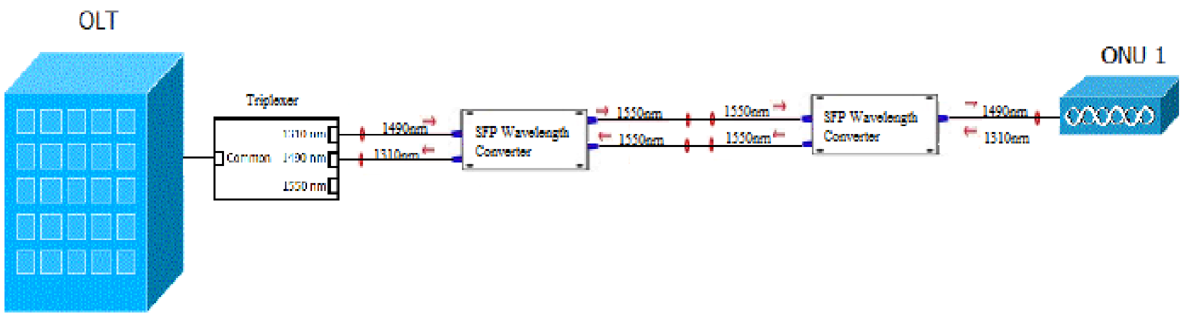

Figure 52: Proposed GPON wavelength conversion

The main objective of this network is to determine the functionality of the SFPs in converting the GPON transmission to another wavelength by introducing a conversion for both downstream and upstream to 1550 nm and then back to its original wavelengths. If successful it demonstrates that it is possible to convert the available transmission to different wavelengths without losing its normal functionality.

To perform this wavelength conversion four SFPs are needed as shown on Figure 52. The first one is the FTLF1319P1BTL as it needs to receive data at 1490 nm and transmit at 1310 nm. Linked to this SFP is the FTLF1621P2BCL which converts the GPON signal at 1490 nm from the other SFP to 1550 nm and receives at 1550 nm the signal which in turn will be converted to 1310 nm in the other SFP.

The 2nd SFP block will function in a similar manner, there is another FTLF1621P2BCL with both transmit and receive wavelengths at 1550 nm but this time linked to a SPL-94B73B-WG which transmits at 1490 nm and receives at 1310 nm on the same fiber.

In order to implement the wavelength converting network, the optical characteristics of each SFP described in chapter 4.1 have to be taken into consideration. As such by measuring the transmitted power of each SFP and reading the datasheets for the sensitivity of each receiver it was clear that some modifications are needed in the network in order to have a stable transmission between OLT and ONU.

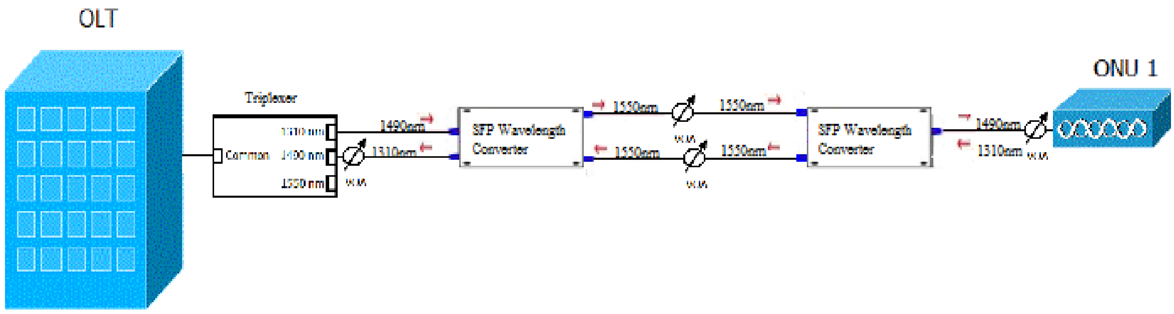

Figure 53: Proposed GPON wavelength conversion with VOAs for receiver sensitivity

The VOAs introduced to the network attenuate the signal being transmitted by the SFPs in order for its power to be within working parameters of the optical receiver, according to their sensitivity.

Due to the GPON equipment not being available when performing these tests, the downstream and upstream transmissions will be done by using lasers operating at the specific GPON wavelengths.

5.3.2 Downstream transmission with a 1490 nm laser

Figure 54 shows the setup used for the downstream transmission:

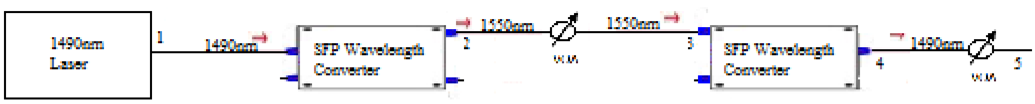

Figure 54: Wavelength conversion with SFPs for downstream transmission

Even though, using this setup it is not possible to determine the full functionality of this technology, it is possible to demonstrate the correct wavelength conversion and power budget necessary without transmitting data.

By utilizing an OSA (Optical Spectrum Analyzer) on the specific points indicated in the circuit (1 to 5) the next figures show the spectrum obtained in each point, and Table 18 indicates the wavelength and power obtained.

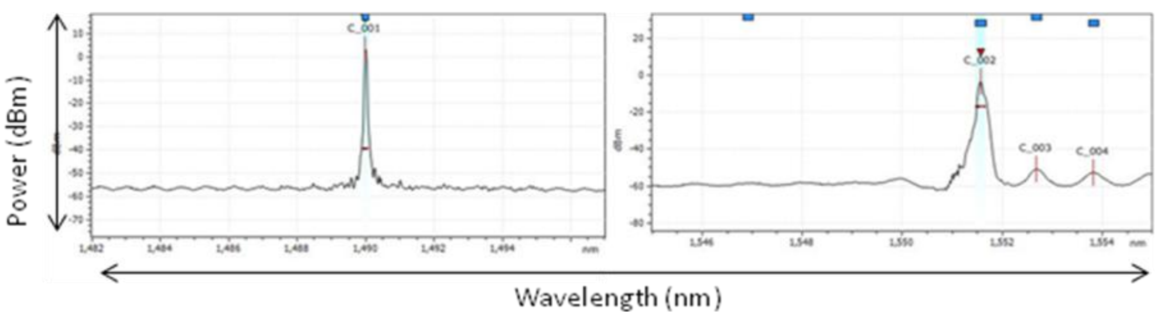

Figure 55: Spectrum obtained from OSA on points 1 and 2 downstream

Figure 55 shows the spectrum obtained on the 1490 nm laser output and the output of the first wavelength converting block at 1550 nm. These spectrums demonstrate that both the laser and the SFP are transmitting at the expected wavelength and that, as mentioned before there is a need to attenuate the signal at point 2 in order for the power obtained at input point 3 to be within the SFP receiver sensitivity.

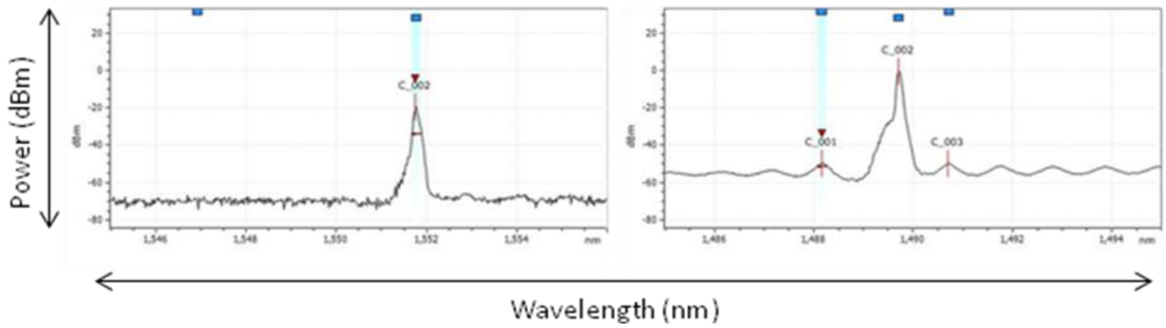

Figure 56: Spectrum obtained from OSA on points 3 and 4 downstream

Figure 56 shows that the power obtained at point 3 is now within the sensitivity range of the SFP and at point 4 the signal is correctly transmitted at 1490 nm. However, there is once again the problem that the power being transmitted at point 4 is above the sensitivity range of the next input (there is none in this case but the network should be done considering the presence of a GPON ONU).

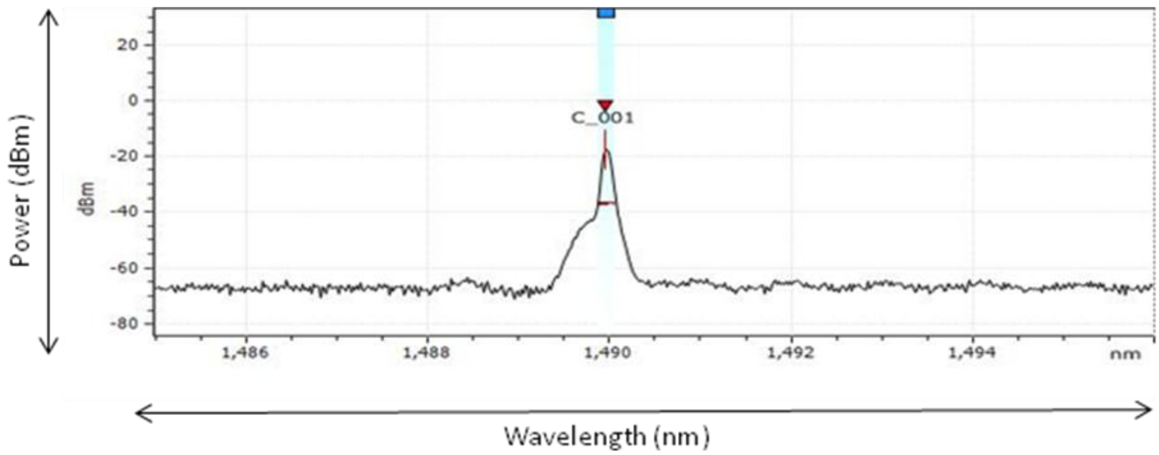

Figure 57: Spectrum obtained from OSA on point 5 downstream

On Figure 57, the final result for downstream is obtained. The signal being transmitted is at 1490 nm and the power measured is within optimal parameters to be received by a GPON ONU.

Position	Name on Spectrum	Wavelength (nm)	Signal Power (dBm)
1	C_001	1489.984	2.59
2	C_002	1551.561	-0.64
3	C_002	1551.758	-17.37
4	C_002	1489.707	1.32
5	C_001	1489.957	-15.37

Table 18: Results Obtained with the OSA on the downstream transmission

Analyzing the results obtained on Table 18, it is possible to observe that the conclusions dedicated to the spectrum obtained in each point are valid as the wavelengths obtained are within expected results and due to the presence of the VOAs when the signal reaches the input point of each SFP the power measured is within accepted values.

5.3.3 Upstream transmission with a 1310 nm laser

As with the downstream transmission, to obtain the relevant results for upstream without having the GPON equipment a laser was used with the necessary wavelength, in this case, 1310 nm.

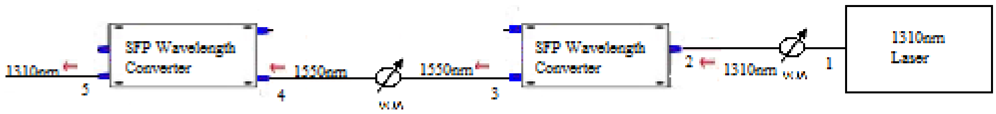

Figure 58: Wavelength conversion with SFPs for upstream transmission

Using this setup the following results were obtained with the OSA:

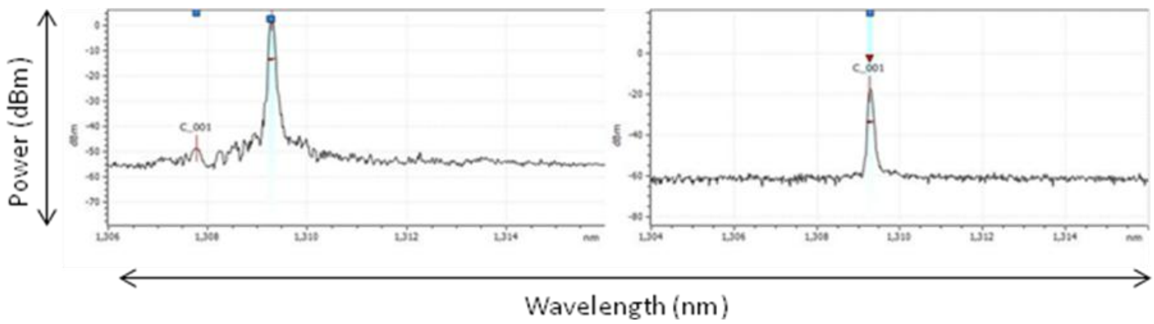

Figure 59: Spectrum obtained from OSA on points 1 and 2 upstream

The spectrums shown on Figure 59 demonstrate that as expected the laser being used is correctly transmitting at 1310 nm however, as the power being transmitted is above the sensitivity of the SFP a VOA was used to attenuate the signal on point 2.

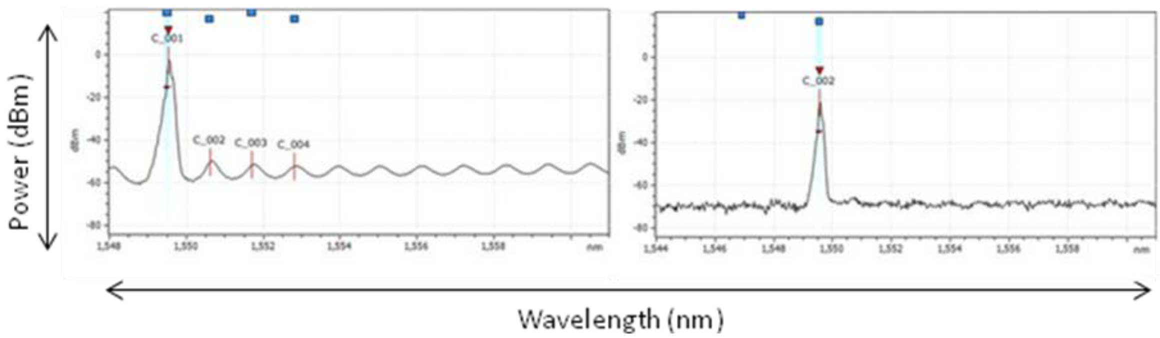

Figure 60: Spectrum obtained from OSA on points 3 and 4 upstream

Figure 60 demonstrates that the spectrums obtained on points 3 and 4 of the upstream transmission are close to the ones obtained at points 2 and 3 on the downstream transmission. This is the expected result as once again the signal is being transmitted 1550 nm by the SFP and being attenuated by a VOA in order to be within the sensitivity of the receiving SFP.

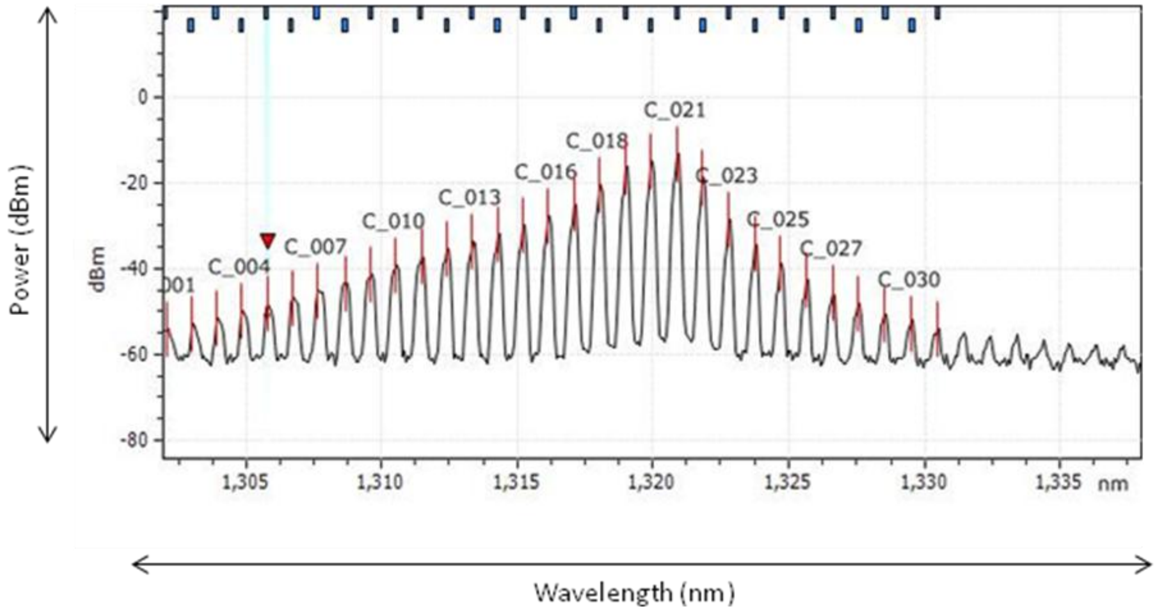

Figure 61: Spectrum obtained from OSA on point 5 upstream

Observing Figure 61, the spectrum obtained on point 5 of the upstream transmission is quite different from the others. In this case, the laser being used by the SFP is a Fabry-Perot resulting in the shown spectrum.

Position	Name on Spectrum	Wavelength (nm)	Signal Power (dBm)
1	C_002	1309.278	2.64
2	C_001	1309.278	-17.74
3	C_001	1549.543	-0.85
4	C_002	1549.557	-19.04

Table 19: Results Obtained with the OSA on the upstream transmission

Observing the results and comparing them to the downstream transmission, the main difference is on the 5th point due to the mentioned Fabry-Perot laser. As the spectrum obtained in the OSA shows that it is not possible to obtain the signal power for a specific wavelength by observing the results in a similar manner as to the other lasers, the signal power for point 5 was obtained using a power meter at 1310 nm. P5 = -8 dBm.

5.4 EPON

Due to a problem in the EPON OLT transmission, it was not possible to perform the same tests done using the GPON network. However, as the expected results of the same tests performed previously are shown in the equipment manual, they will be displayed here for comparison with the GPON results.

Figure 62 shows how the network is implemented using the equipment described in chapter 4.3:

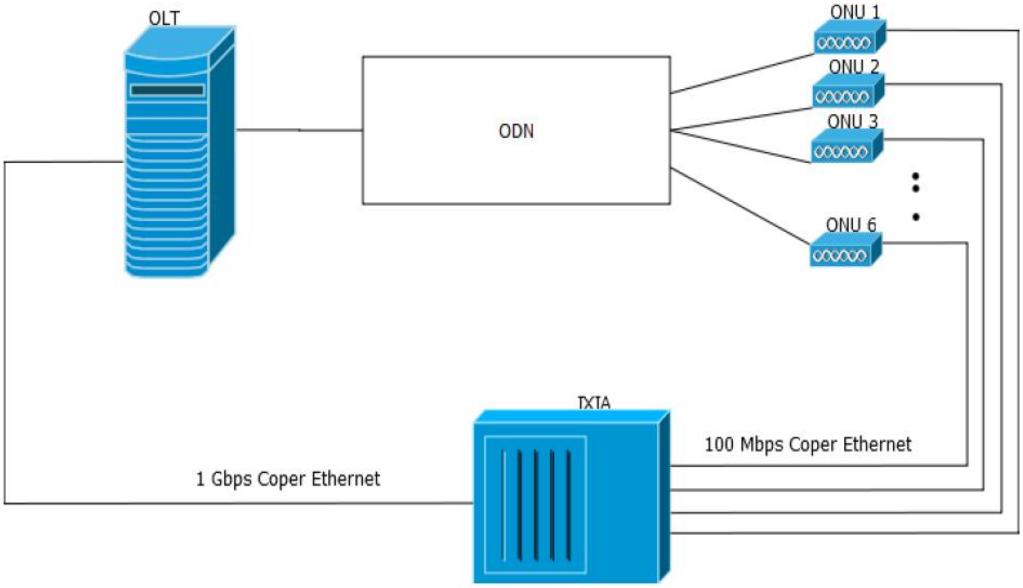

Figure 62: EPON data transmission using IXIA

5.4.1 EPON Transmission Rate

As shown above each ONU is limited to a 100 Mbit/s Ethernet card but as with the GPON transmission it is not possible to transmit data at maximum line rate without packet loss as demonstrated on Figure 63:

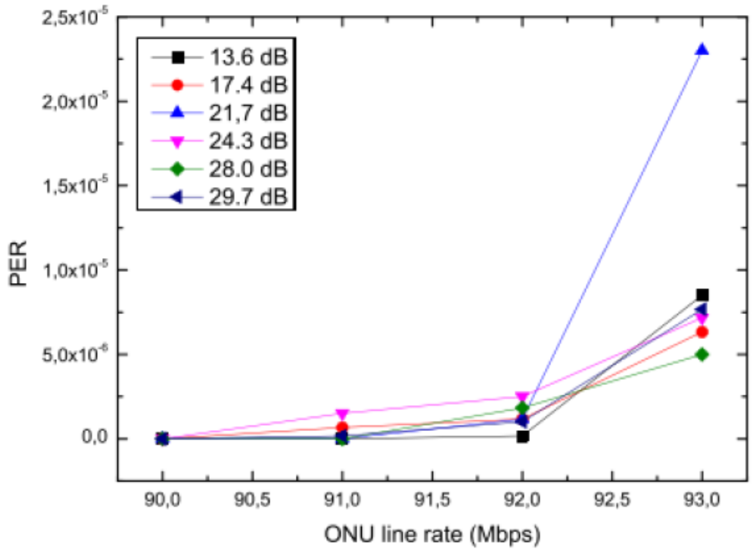

Figure 63: EPON line rate test

There is no packet loss at line rates below 90 Mbit/s but increasing it results in increased losses up to around 92 Mbit/s where the packet loss becomes relevant especially at higher power budgets.

5.4.2 EPON Power Budget

As a last comparison to the GPON network the results for maximum power budget will be displayed for both downstream and upstream transmission in Figure 64 for downstream and Figure 65 for upstream:

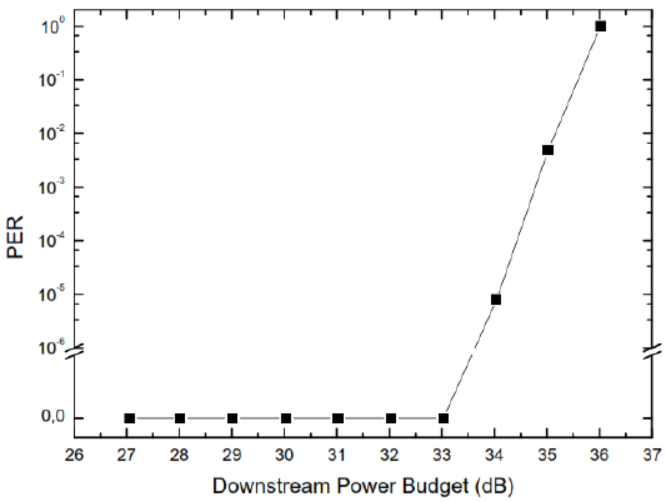

Figure 64: EPON downstream power budget

On the upstream there is no loss up to a power budget of 33 dB but increasing the value results in high packet loss.

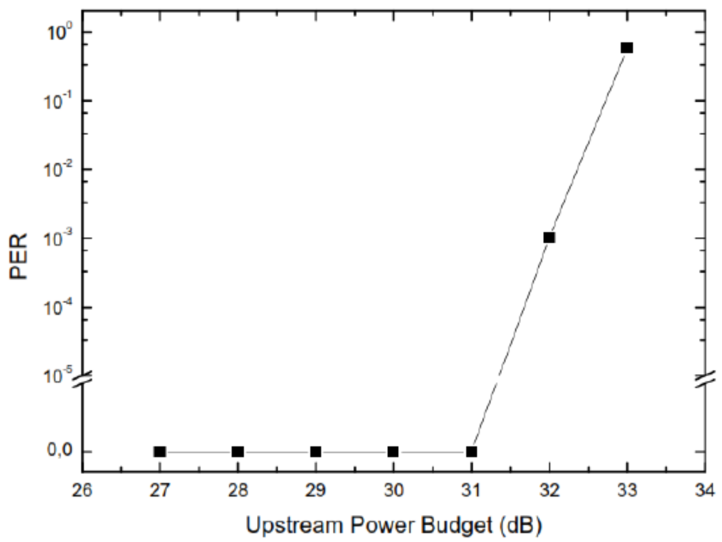

Figure 65: EPON upstream power budget

In terms of upstream transmission, the power budget is lower as there is packet loss for a power budget superior to 31 dB.

6. Simulations

In this chapter, some of the circuits described in chapter 6 will be tested using VPI Transmission Maker 9.0. Using this program it is possible to simulate the results of implementing some of the discussed networks while effortlessly adapting some of its main parameters.

6.1 GPON simulation

The following figure shows the GPON network created in VPI to simulate the results obtained when using such a network.

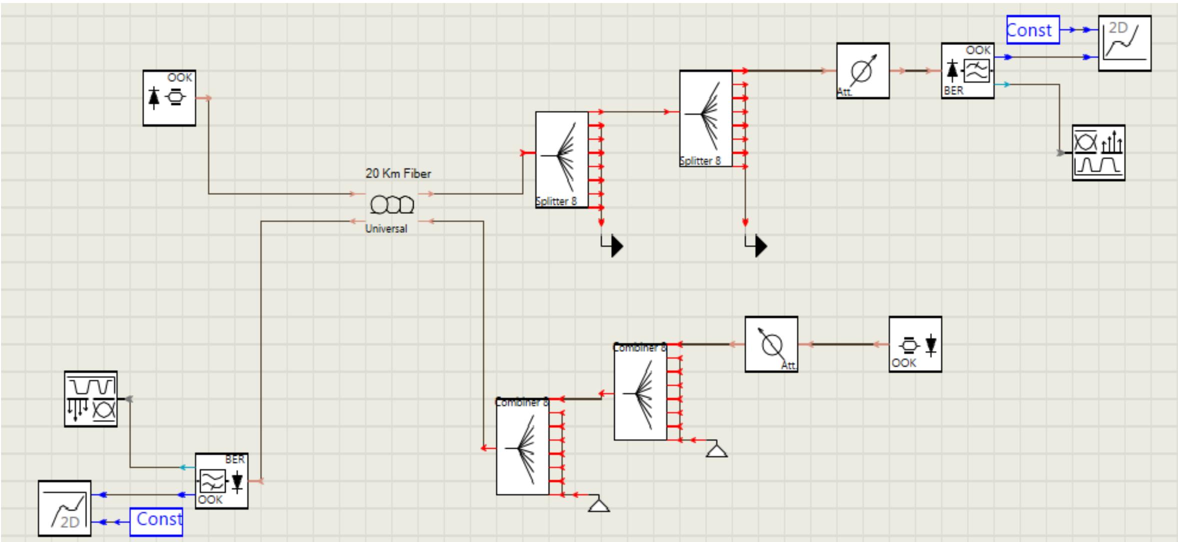

Figure 66: GPON network in VPI

The main purpose of this simulation is to demonstrate the BER obtained for both downstream and upstream. In order to better approximate this network to a GPON network present in the field, a 20 km fiber and a 1:64 splitter (divided in two 1:8 splitters for a better comparison to the laboratory network) was used.

The most relevant parameters in this simulation are the following:

- Downstream Wavelength: 1490 nm
- Downstream Transmitter Power: ~0 dBm
- Downstream bit rate: 2.5 Gbit/s
- Upstream Wavelength: 1310 nm
- Upstream Transmitter Power: ~0 dBm
- Upstream bit rate: 1.25 Gbit/s
- Thermal Noise on receivers: 0.9e-11 A/Hz^(1/2)

By varying the attenuation present in the network using the VOAs, it is possible to do a similar study to the one demonstrated on the previous chapter. The following results obtained with VPI Photonics Analyzer demonstrate the BER obtained with the attenuation varying between 3 and 18 dB.

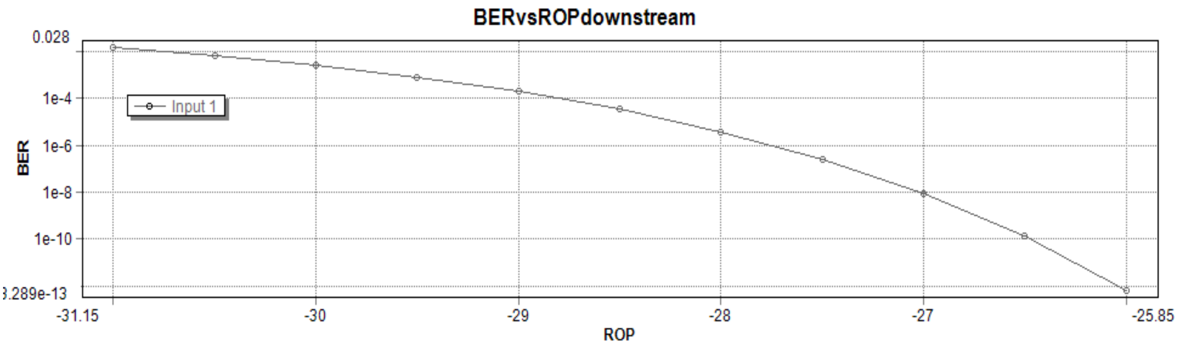

Figure 67: GPON network BER vs. ROP downstream results

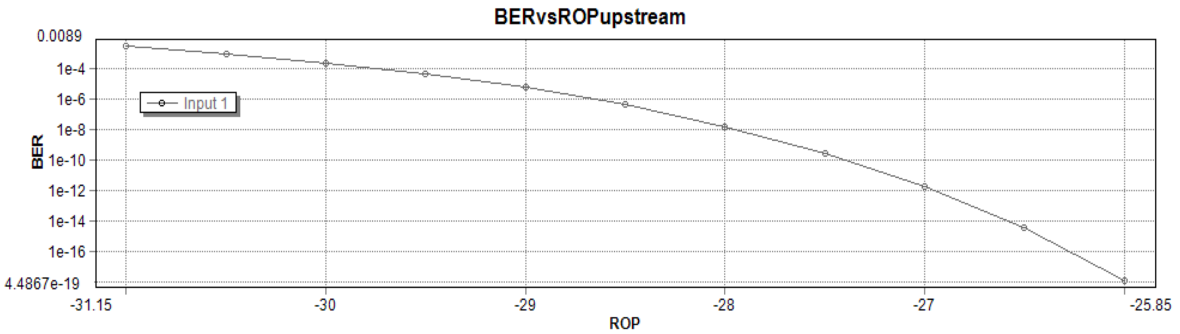

Figure 68: GPON network BER vs. ROP upstream results

Observing the graphics above it is possible to perceive that there is a higher sensitivity in the upstream transmission then in the downstream. For a BER of -10 the ROP (Received Optical Power) on the downstream transmission is around -26.5 dBm while for the upstream transmission it is approximately -27.5 dBm.

In order to better compare these results a graphic was made in Matlab displaying simultaneously both signals:

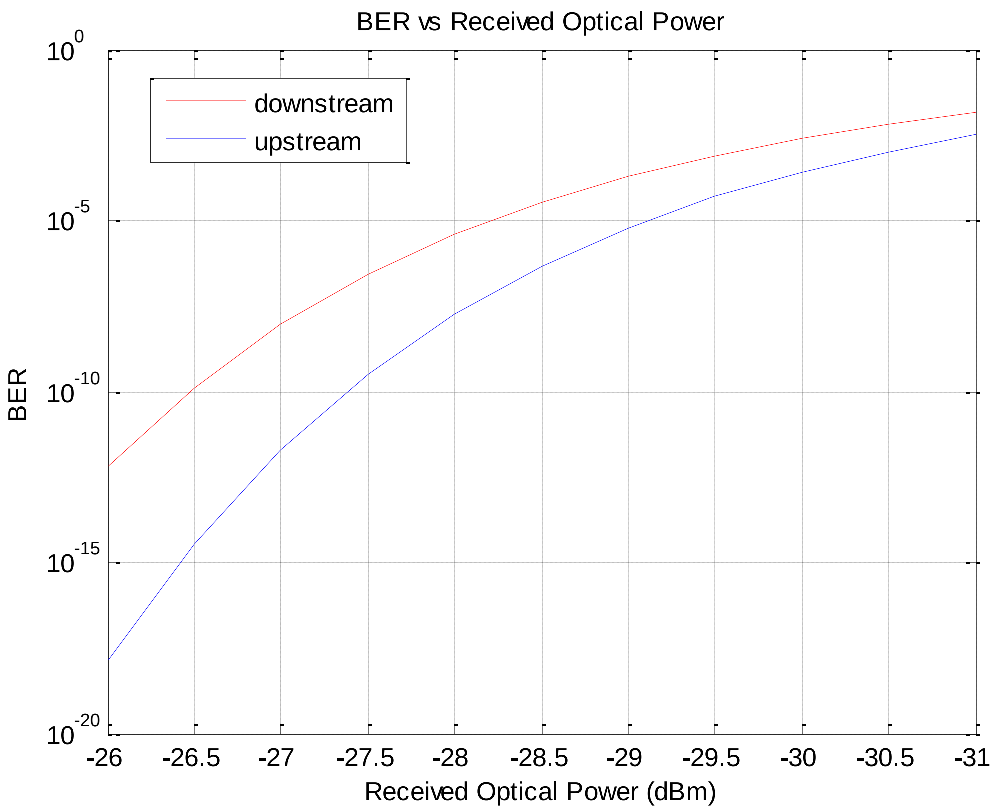

Figure 69: Matlab comparison of downstream and upstream BER vs ROP

Another simulation was made where the 20 km fiber was removed in order to discern if the difference was measurable. The results however were almost identical, as non linear effects are not being considered in this simulation and the fiber dispersion barely impacts the results.

6.2 *Wavelength Converter*

The wavelength conversion network presented in chapter 5 was simulated in VPI by using the circuit shown below:

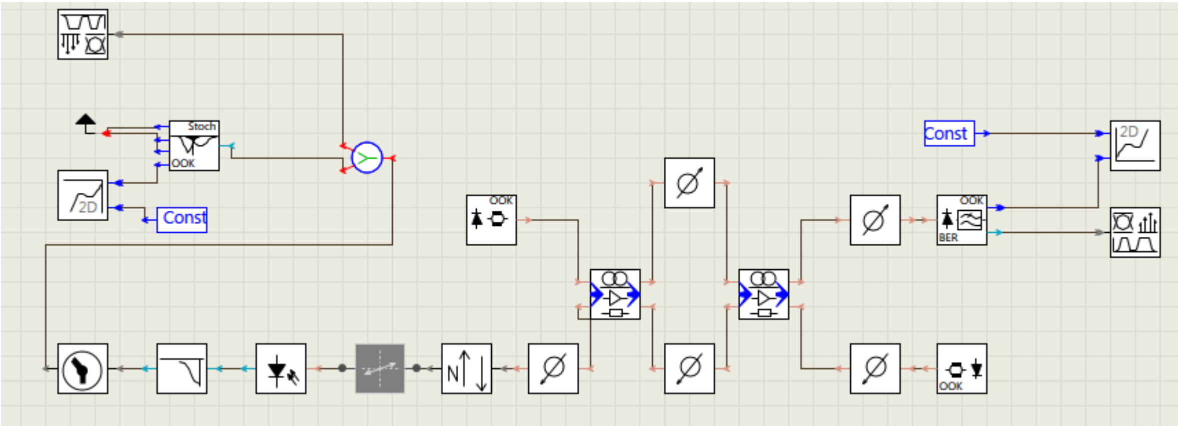

Figure 70: Wavelength Converter in VPI

As the SFPs used are not present as a module in VPI, there was a need to create new modules performing the same function as the SFP converters used in the laboratory.

The first module created is shown on Figure 71:

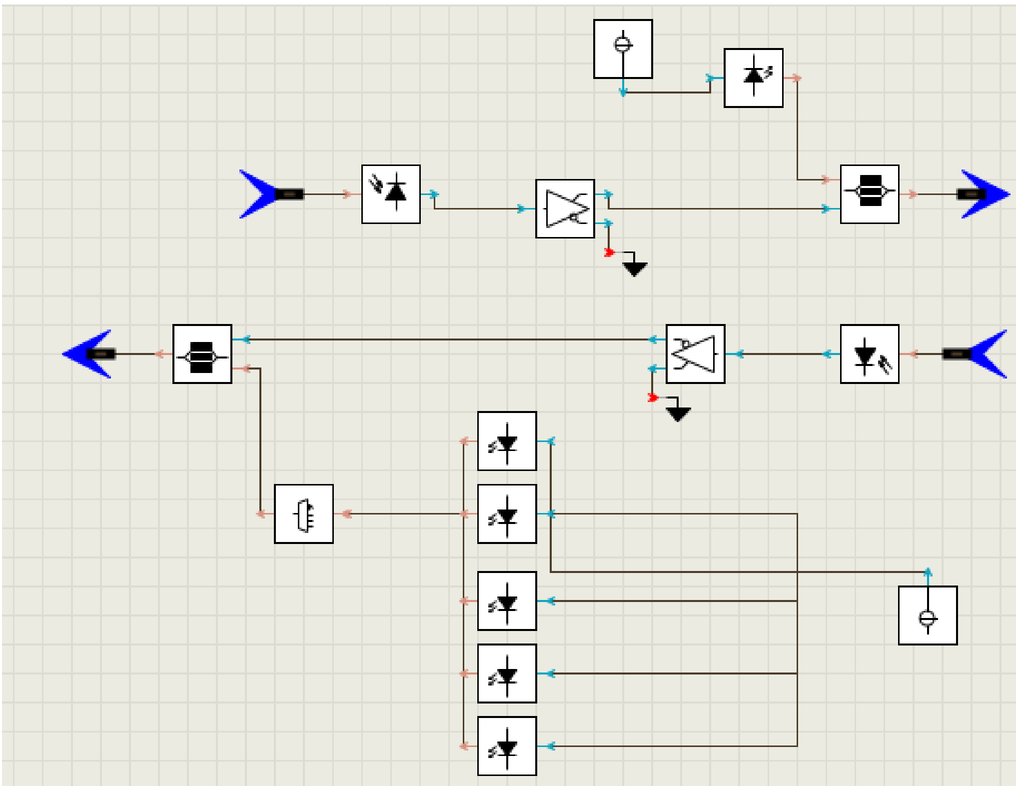

Figure 71: First SFP module created in VPI

This module simulates the first SFP block consisting of the 1490 to 1550 nm downstream wavelength converter and 1550 to 1310 nm upstream. As the laser transmitting at 1310 nm is a Fabry-Perot laser which is not available directly as an optical source on VPI, to simulate its transmission five lasers were used in order to create a similar result as to the one shown on Figure 61 .

The second SFP module is shown on Figure 72:

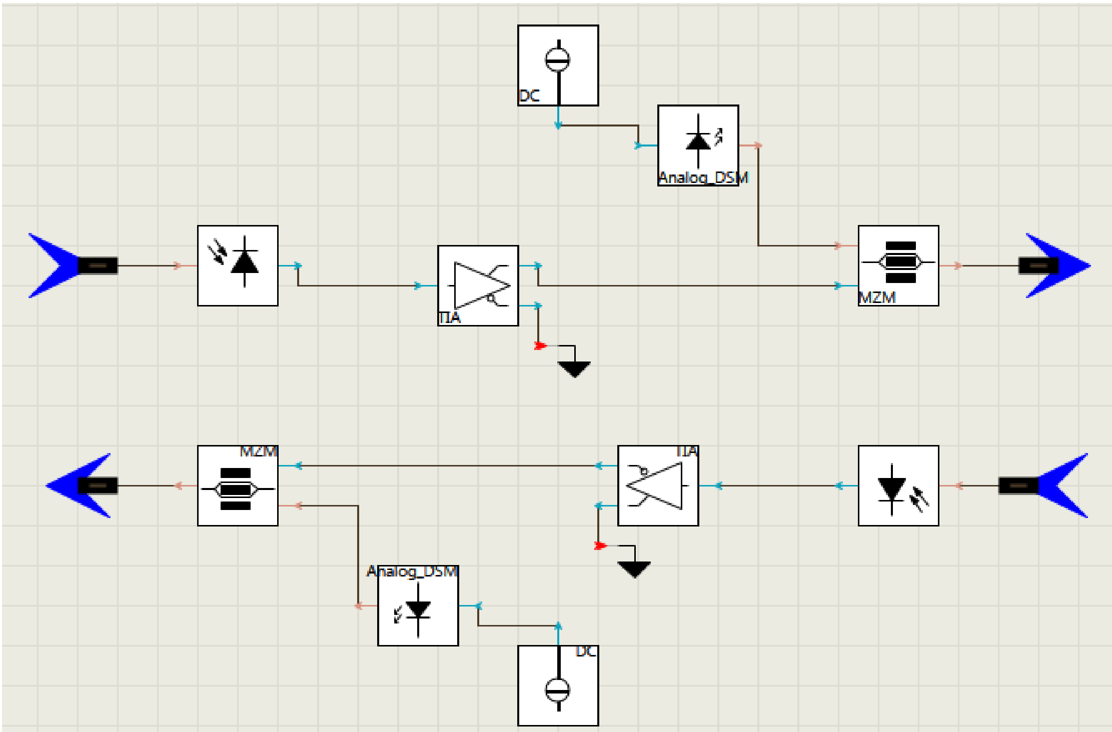

Figure 72: Second SFP module created in VPI

This second module simulates the other conversion of the network where the downstream transmission at 1550 nm is converted to 1490 nm and the upstream signal being transmitted at 1310 nm is converted to 1550 nm.

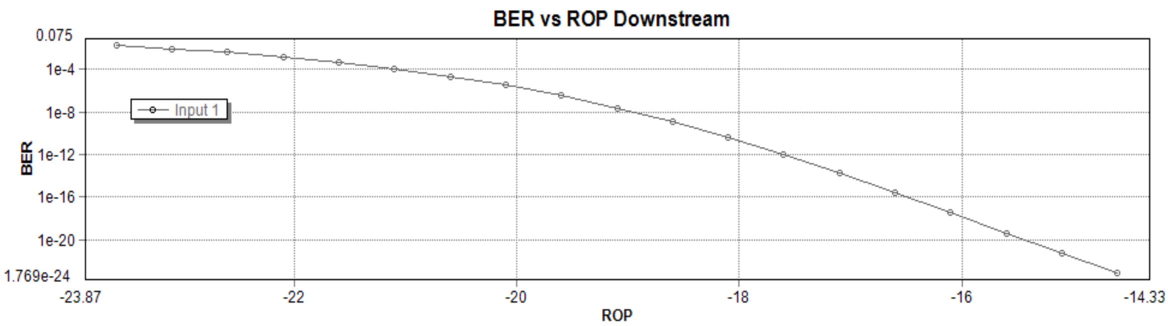

Figure 73: Wavelength Converter BER vs. ROP downstream results

Figure 73 shows that the signal in this network degrades faster than on the GPON network. For a BER of -10 the ROP is only approximately -18.5 dBm while on the GPON it was -26.5 dBm. This degradation was expected since there are two wavelength conversions between the transmitter and receiver and even though the sensitivity of the transmitter is lower it is demonstrated that is possible to transmit data on the downstream direction.

In terms of upstream transmission however it was not possible to obtain results possibly due to the fact that as mentioned before a Fabry-Perot laser is not available as an optical source. The solution of using several DFB lasers to simulate the Fabry-Perot results in a spectrum similar to the one obtained in the OSA but might result in the data being lost. While the upstream results were not obtained, it is expected that as for the downstream transmission the signal in this case should degrade even faster than before when compared to the GPON transmission without wavelength conversion due to the last conversion being made by the Fabry-Perot laser which has a higher linewidth than a DFB laser.

7. Conclusions and Future Work

7.1 Conclusions

As indicated in Chapter 1, due to the ever increasing need for greater bandwidth and better options in terms of transmitting data, this dissertation described the available options currently present in the market by indicating its main characteristics and comparing the different solutions in Chapter 2.

This chapter also evaluates the possible implementations for a NGPON2 network, it was demonstrated that even though, some of the options being studied across the globe might never be implemented successfully, there is a great interest in demonstrating the need for a new option for access networks.

Using WDM-PON as the main focus of this dissertation, several possible implementations of such a network were presented in Chapter 3 to illustrate that despite the high cost inherent to this solution there are various possible ways to implement a WDM-PON network. After describing how to create a WDM-PON network using tunable components, the focus shifted to a possible implementation using SFPs to convert the normal wavelengths being used in a GPON network.

Chapter 4 serves to indicate the equipment being used in the laboratory and their main parameters relevant to the tests that are going to be performed.

The GPON results presented in Chapter 5 are the basis of this work as it demonstrates that despite the limitations imposed on the network by the IXIA, it is still possible to test several parameters present in such a network currently used in FTTH solutions. In terms of EPON, it was not possible to perform the in depth tests done with the GPON due to a problem in the EPON OLT but still the results indicated which were present in the equipment manual supplied by IT are a good basis for a comparison to the expected results. With the available GPON equipment tested in terms of line rate and power budget, the next step was implementing the SFPs for wavelength conversion. By having the GPON downstream and upstream transmissions being converted to another wavelength and back without loss in data it would be shown that is possible to implement a WDM-PON network using this components. Unfortunately the IXIA was not available to perform the data transmission in this new network but it was still possible to create a working network in terms of power budget with the transmission being a possible future test performed using this network as a start.

In terms of simulations done using VPI transmission maker in Chapter 6, a similar GPON network to the one used at the laboratory was characterized in terms of power budget without being limited in terms of line rate by the IXIA. Also in this chapter, a wavelength converting network was created to test the influence of the SFPs in terms of degrading the BER.

7.2 Future Work

The first proposal is introducing the GPON and IXIA equipment in the Wavelength converting network in order to test its possible implementation by defining the amount of data loss when changing wavelengths.

If successful there are several other possible implementations to further the study of this technology. By implementing this equipment with a WDM network comprised of tunable components it would be possible to test the functionality of the SFPs for various possible wavelengths and create a network where several GPON signals are being transmitted at different wavelengths.

Another proposal would be to continue the simulation work presented in VPI in order to further test how far the network supports the different parameters present on the SFPs. Varying several of these parameters it should be possible to characterize the range of values possible for each variable in order to find the optimal values.

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